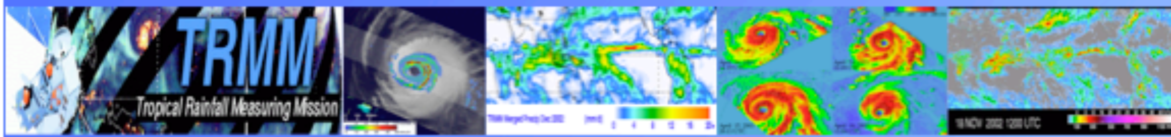
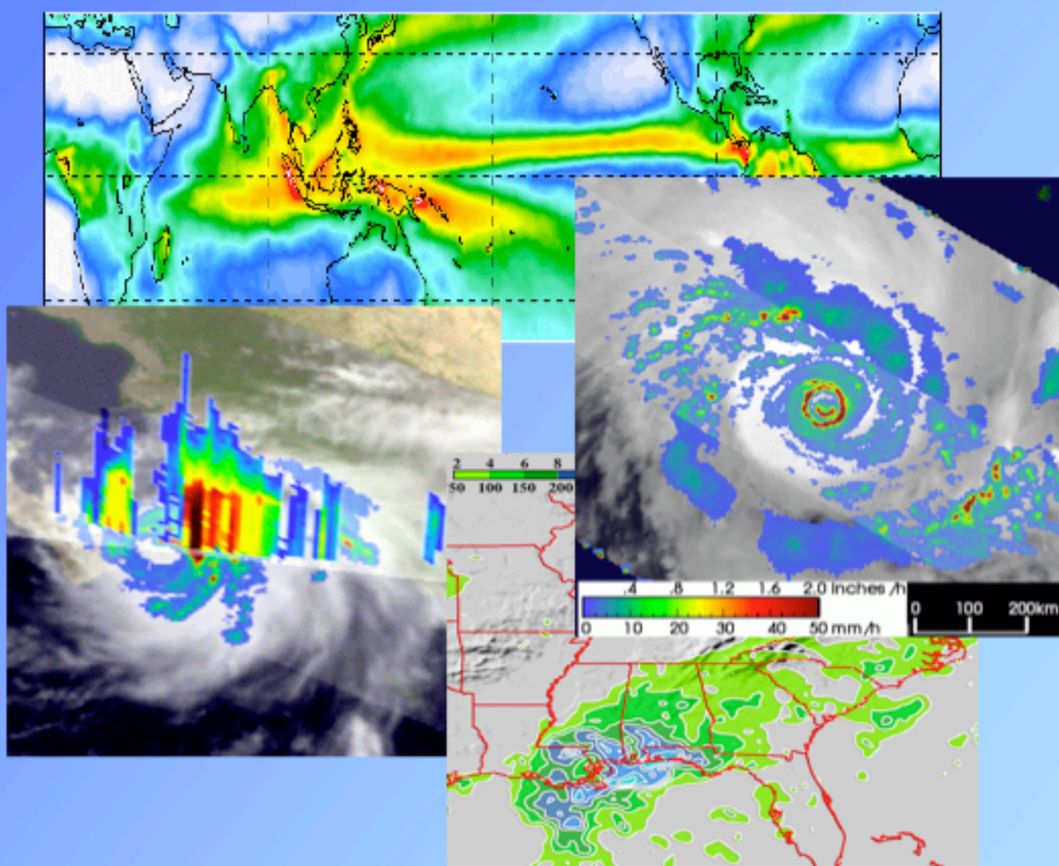


Tropical Rainfall Measuring Mission
TRMM

Senior Review Proposal
2005



TRMM Senior Review Proposal

Executive Summary

The Tropical Rainfall Measuring Mission (TRMM), launched in late 1997, is a joint mission between NASA and JAXA, the Japanese space agency. **The first-time use of both active and passive microwave instruments and the precessing, low inclination orbit (35°) has made TRMM *the world's foremost satellite for the study of precipitation and associated storms and climate processes in the tropics*.** TRMM has met and exceeded its original goal of advancing our understanding of the distribution of Tropical rainfall and its relation to the global water and energy cycles. TRMM has evolved from an experimental mission focusing on tropical rainfall climatology into the primary satellite in a system of research and operational satellites for analyzing precipitation on time scales from 3-hr to inter-annually and beyond. Now TRMM is poised after seven years of success to provide exciting new, critical research through extension of its data set for up to seven years and even the potential of overlap with the forthcoming (2010) Global Precipitation Measurement (GPM) mission. **The overall science objective of an extended TRMM mission is *to determine the time and space varying characteristics of tropical rainfall, hydrometeor structure and associated latent heating and how these characteristics are related to variations in the global water and energy cycles*.** This TRMM goal is at the heart of NASA's Earth Science strategy and the answering of key science questions for the Water and Energy Cycle focus area, i.e., *"How are global precipitation, evaporation and the water cycle changing?"* and *"How will water and energy cycle dynamics change in the future?"* Having a long, accurate record of quasi-global precipitation characteristics is critical to achieving NASA Earth Science goals. The TRMM satellite and the associated science program are ready, and eager, to provide that data and science to NASA and the world research community. The **National Academy** has already spoken on this subject. In a recent independent assessment of the benefits of extending TRMM they clearly stated that **"*Considering the past and expected scientific and operational contributions presented in this report, important benefits would be obtained if TRMM were extended until it runs out of fuel.*" (NRC, 2004).**

Significant scientific accomplishments have already come from TRMM data, including reducing the uncertainty of mean tropical oceanic rainfall, a documentation of regional, diurnal, and inter-annual variations in precipitation characteristics, the first estimated profiles of latent heating from satellite data, improved climate simulations, increased knowledge of characteristics of convective systems and tropical cyclones, and new insight into aerosol/precipitation relations and the impact of cities on rainfall distributions. The availability of real-time TRMM data has led to applications and operational use of TRMM data, primarily in the monitoring of tropical cyclones, in hydrological applications and in assimilation of precipitation information into numerical forecast models.

Extension of TRMM will result in: *1) an improved climatology of precipitation characteristics, especially extremes; 2) improved diagnosis and closure of global (and regional) water cycles; 3) diagnosis and testing of inter-decadal and trend-related processes in the water cycle; 4) assessment of impact of humans (e.g., cities and aerosols) on rainfall characteristics and processes; 5) robust determination of convective system, tropical cyclone, and lightning characteristics; 6) advances in hydrological applications over land (basin-scale assessments, water management); 7) improved modeling of the global water/energy cycles for weather/climate predictions; and 8) improved monitoring and forecasting of tropical cyclones, floods and other hazardous weather.*

The TRMM satellite and its instruments are in excellent shape and if all the station-keeping fuel on board is used to maintain science operations, TRMM data could be available into 2012 and provide an extremely valuable overlap with GPM. TRMM flight operation and data processing costs have been significantly reduced for the extension period. Science and data processing costs will continue with or without TRMM, due to preparation for GPM and continued generation of related precipitation products. Continuation of TRMM, therefore, will mainly require only the additional cost of continuing flight operations ($4M/yr). ***Thus a multi-year extension of TRMM is a very high payoff for science and applications, but at a very low additional cost to NASA.***

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Science Section

1. TRMM MISSION BACKGROUND

1.1 Introduction

The Tropical Rainfall Measuring Mission (TRMM) is a joint project between NASA and the Japanese space agency, JAXA. It was launched on November 27, 1997 and continues to provide the research and operational communities unique precipitation information from space well into 2005. The first-time use of both active and passive microwave instruments and the precessing, low inclination orbit (35°) make TRMM the world's foremost satellite for the study of precipitation and associated storms and climate processes in the tropics. Complete information about the TRMM mission can be found at U.S. TRMM web site http://trmm.gsfc.nasa.gov.

The overarching TRMM science goal is to advance our knowledge of the global energy and water cycles by observing time and space distributions of tropical rainfall, hydrometeor structure and associated latent heating distributions. TRMM has met and exceeded this research goal and is *the* major observational success of NASA's Water and Energy Cycle research program over the last decade. However, TRMM's work is not nearly done. Continuation of TRMM is critical to the future success of NASA's water and energy cycle research through exploitation of TRMM's extended data set, which with each additional year becomes increasingly valuable for climate variability and climate change studies. Extension of TRMM also provides the potential of a cross-calibration overlap with the Global Precipitation Measurement (GPM) mission, providing the possibility of an unprecedented observational record of accurate precipitation with which to probe climate variability and change within the water cycle from 1997 to 2015 and beyond.

The primary TRMM instruments are the *Precipitation Radar (PR)*, the first and only rain radar in space, and the *TRMM Microwave Imager (TMI)*, a multi-channel passive microwave radiometer, which complements the PR by providing total hydrometeor (liquid and ice) content within precipitating systems. The *Visible Infrared Scanner (VIRS)* is used to provide the cloud context of the precipitation structures and is used as part of a transfer strategy to connect microwave precipitation information to infrared-based precipitation estimates from geosynchronous satellites. These three instruments form the original TRMM rain package and are used singly and jointly to understand precipitation processes, structure and climatology. In addition, the *Lightning Imaging Sensor (LIS)*, an EOS-funded instrument, has complemented the rain sensors and improved understanding of convective dynamics and provided a climatology of global lightning flash rates. The CERES Earth radiation budget instrument on TRMM failed after eight months of flight and is not addressed here. Table 1 summarizes the characteristics of the TRMM rain instruments and Fig. 1 shows the swath geometry of the various instruments. Additional information on the TRMM instruments is given in Section 4.2.

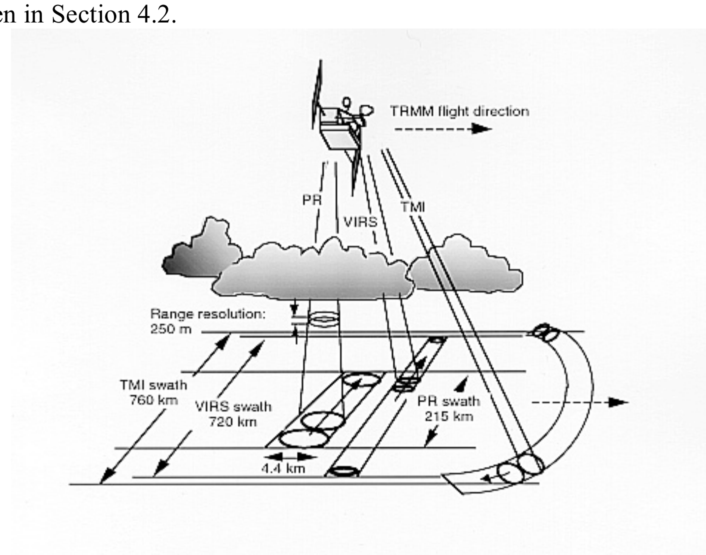

Fig. 1. Schematic of TRMM satellite and scanning geometries of three rain package instruments.

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Table 1. TRMM Sensor Summary – Rain package

Microwave radiometer (TMI)	Radar (PR)	Visible and infrared Radiometer (VIRS)
10.7, 19.3, 21.3, 37.0, and 85.5 GHz (dual-polarized except for 21.3: vertical only)	13.8 GHz	0.63, 1.61, 3.75, 10.8, and 12 μm
11 km X 8 km field of view at 37 GHz	5-km footprint and 250-m vertical resolution	2.5-km resolution
Conically scanning (53^0 inc.)	Cross-track scanning	Cross-track scanning
880-km swath	250-km swath	830-km swath

The set of TRMM precipitation products are listed in Table 2. Multiple rain algorithms were developed, inter-compared and used for analysis because of the difficulty of making this remote sensing observation, the strengths and weaknesses of the various approaches and the multiplicity of research applications. These different algorithm methodologies exploit different physical attributes of hydrometeors (scattering vs. emission, reflectivity vs. extinction, vertical structure). The availability of multiple techniques aids in understanding and verification and has led to significant advances in the remote estimation of precipitation. The multi-satellite products utilize the TRMM information to calibrate, or adjust, the rain estimates from other, less capable instruments and then combine all the satellite estimates into multi-satellite analyses at high time resolution (~ 3 hr). Brief descriptions of the main TRMM algorithms are given in an Appendix.

Table 2. Primary TRMM Rain Products

Name	Reference No.	Purpose
Level2 data		
Surface cross section	2A21	Radar surface scattering cross section/total path attenuation.
PR rain type	2A23	Type of rain (convective/stratiform) and height of bright band.
TMI profiles	2A12	Surface rainfall and 3D structure of hydrometeors and heating over TMI swath.
PR profiles	2A25	Surface rainfall and 3D structure of hydrometeors over PR swath.
PR-TMI combined	2B31	Surface rainfall and 3D structure of hydrometeors derived from TMI and PR simultaneously.
Level-3 data		
TMI monthly rain	3A11	Monthly 5^o rainfall maps-ocean only.
PR monthly average	3A25	Monthly 5^o rainfall and structure statistics from PR.
PR-TMI monthly average	3B31	Monthly accumulation of 2B21 products and ratio of this product with accumulation of 2A12 in overlap region.
TRMM Multi-satellite	3B42	Multi-satellite precipitation data calibrated by TRMM,3-hourly, 0.25^o resolution.
TRMM Multi-satellite/gauge	3B43	3B-42 and gauge products-data merged into single rain product, monthly, 0.25^o resolution.

1.2 History—Development, Launch, Boost

The TRMM concept was developed in the 1980's, driven by a scientific need for climatological precipitation information to understand the global water cycle and for investigation of atmospheric convective systems, cyclonic storms and precipitation processes. The first of a series of TRMM workshops was held in late1986, with results described in a report (Simpson, 1988) and journal article (Simpson et al. 1988). During the 1980's discussions and joint work between U.S. and Japanese scientists in the development and use of an experimental aircraft precipitation radar evolved toward interest in a joint satellite project.

The TRMM satellite was built in-house at Goddard with the instruments delivered from manufacturers (including the PR from Japan). The assembled satellite was then shipped by aircraft to Japan where it was successfully launched from JAXA's Tanegashima launch site on an H-II rocket on November 27, 1997. The *TRMM orbit altitude originally was 350 km* and the inclination is 35°, so that the satellite covered the tropics and the southern portions of both Japan and the United States. The precessing orbit also passes through all the hours of the day, thereby giving a unique data set for observing the diurnal cycle of rainfall. The first full month of data was January 1998. Although the CERES instrument failed after eight months, all the precipitation package instruments (PR, TMI, VIRS) and the LIS have functioned perfectly for over seven years.

TRMM was originally designed to provide data for a minimum of three years, with a goal of five years. Because of its low altitude (necessary for high signal for the radar and for fine spatial resolution of highly variable rain fields) TRMM has a small propulsion system used to maintain near-constant altitude against the effect of atmospheric drag. Although launched with over 800 kg of fuel for the propulsion system, by early 2001 (three years into the mission) TRMM scientists faced an early end of the mission in 2002 or 2003 due to lack of fuel. *After careful analysis of the benefits and drawbacks, the TRMM science teams (U.S. and Japan) proposed increasing the orbit altitude by about 50 km in order to decrease atmospheric drag and extend mission life.* After extensive review NASA and JAXA agreed to the mission extension plan and ordered the boost to the higher altitude. *The boost to 402.5 km (+/- 1.0 km) was carried out in August 2001* and TRMM has operated at that altitude since that date. The exact altitude chosen (402.5 km) is related to the PRF of the PR.

Although TRMM started as an experimental mission to study tropical rainfall, and was originally expected to last only 3-5 years, it has evolved into the primary, or core, satellite in a system of research and operational satellites monitoring precipitation on time scales from 3-hr to inter-annually and beyond. TRMM's role as the primary satellite in this system is because of the high quality precipitation information available from its active-passive combination of instruments and the inclined orbit visiting the entire diurnal cycle with frequent intersections with polar-orbiting satellites. Today TRMM data are used to calibrate and integrate precipitation information from multiple polar orbiting satellites/instruments (AMSR on Aqua, SSM/Is on DoD/DMSP and AMSU on NOAA platforms) and geosynchronous satellites into merged precipitation analyses being used both for research and applications. The real-time availability of TRMM products has also resulted in the use of TRMM data by operational weather agencies in the U.S. and around the world for monitoring and forecasting of tropical cyclones, floods and other hazardous weather.

1.3 National Academy Review

At the request of NASA, the National Academies (NA) in December 2004 completed an assessment of the scientific accomplishments of TRMM and the benefits of extending the TRMM mission. This NA review provides the Senior Review a high-level external assessment of the scientific value of TRMM independent of other NASA missions. The key findings are summarized in this section.

A key conclusion from the Executive Summary of the NA report: "*Considering the past and expected scientific and operational contributions presented in this report, important benefits would be obtained if TRMM were extended until it runs out of fuel.*" The report also urges careful consideration of the benefits, risks and costs of extending TRMM in terms of the decision on whether to execute a controlled re-entry of the satellite.

The NA report summarized the research reasons for continuation of TRMM from their viewpoint in Conclusion 4.3 from that report: ***"CONCLUSION 4.3****: From the perspective of anticipated research contributions, TRMM is worth continuing for six primary reasons:*

1. TRMM provides a unique complement of measurements. Specifically, the precipitation radar, the passive microwave imager, and the visible and infrared instruments provide a powerful overlap of precipitation, cloud, and water vapor measurements and the lightning imaging sensor helps isolate intense convective cells. In addition, the TMI permits sea surface temperature measurement through clouds at high spatial resolution. Continuation of the *mission is vital to the future development of spaceborne precipitation radar technology, especially in the evaluation of radar technology life cycle.*

2. Mission extension creates the opportunity for cross-calibration, validation, and synergy with sensors on future missions, such as CloudSat and the A-Train satellite series, National Polar-orbiting Operational Environmental Satellite System's Conical Scanning Microwave Imager/Sounder, and Global Precipitation Measurement core satellite and other constellation satellites.

3. TRMM's unique low-inclination, low-altitude, precessing orbit enhances science by providing unique spatial and temporal information that fills the gaps in data from other current and upcoming polar-orbiting satellite sensors.

4. TRMM data will enhance field experiments and programs (e.g., TCSP, AMMA, GEWEX, THORPEX, TEXMEX-II), tropical cyclone research (including tropical cyclone forecasting), and development of cloud-resolving models.

5. A longer record is required to collect enough examples to cover the parameter space of synoptic variability more fully. For example, over the first six years of TRMM data, the TMI instrument passes within 750 km of storm centers during one of every eight orbits, whereas PR observes within 250 km of the center during one of every 25 orbits. The narrow swath of the PR and the rare occurrence and great variability of tropical cyclone structure, intensity, and precipitation amount strongly argues for mission extension to increase sample sizes for statistical analyses.

6. Longer TRMM data records will better characterize tropical seasonal-interannual climate variability in general and the El Niño-Southern Oscillation (ENSO) cycle in particular. ENSO is the dominant mode of global interannual climate variability. TRMM provides quantitative ENSO-related tropical rainfall anomalies that are needed to improve our understanding of both the local and remote effects of this phenomenon, and ultimately to make better predictions of its socioeconomic effects in both the tropics and extratropics."

In terms of <u>operational use</u> of TRMM data, the NA panel stated that: "***CONCLUSION 4.4*** *TRMM's reliability combined with the value of TRMM data to operations shows the satellite's potential as an operational system. From a perspective of anticipated operations contributions, TRMM is worth continuing for three primary reasons:*

1. TRMM data from the TMI and PR sensors have a demonstrated capability (for TMI) or potential capability (for PR) to improve the weather forecasting process, especially for monitoring and forecasting the tracks and intensity of tropical cyclones and the intensity of rainfall they yield.

2. Continuation of the TMI data stream would enable modelers and forecasters to continue to improve the overall numerical weather prediction process, (i.e., model development and validation, forecast initialization, and forecast verification). This includes use of TMI in calibrating similar data from other microwave sensors and contributes to improved global, as well as tropical, precipitation monitoring and prediction.

3. PR data are an underexploited yet unique resource. Having them available in near real time for an extensive period of time would foster investment of time and effort to make full use of PR data in the forecasting process."

2. SUMMARY OF TRMM ACCOMPLISHMENTS TO DATE

TRMM's enormous success is related to its two unique attributes that make it ideal for observing tropical rainfall systems: (1) its suite of *complementary observing instruments*, and (2) its *orbit characteristics*. TRMM provides a complementary suite of active and passive sensors flown on a single platform, providing the most complete view of precipitation. Due to its complement of instruments, TRMM has been called the "flying rain gauge", i.e., ***the space standard for precipitation observation***. The TRMM observing system employs the only precipitation radar in space, the PR, which provides the most direct method of observation of precipitation and its vertical distribution (i.e., enabling a three-dimensional view of precipitation). Efforts to resolve disagreements between precipitation estimates from the PR and the passive microwave TMI are only now reaching the point where TRMM's potential to act as a global rainfall reference standard is being utilized. *Without the PR in space, there will be no similar opportunity for calibration with an active sensor until GPM is launched.*

TRMM's unique orbital characteristics enable it to fill temporal and spatial sampling gaps from all current and soon-to-be-launched microwave satellite sensors. TRMM's 35-degree inclination, low altitude (402.5 km), and non-sunsynchronous orbit provide multiple benefits when compared with the space and time sampling dictated by standard polar orbiting trajectories. The low-latitude orbit permits rapid updating in the tropical belt and the precessing nature of the orbit allows for sampling of the diurnal variation of precipitation.

One measure of TRMM's contribution is the large number of refereed publications that mention TRMM (see Fig. 1). The TRMM launch triggered a virtual flood of research that has led to significant improvements in our understanding of the hydrologic cycle and the climate system and of tropical weather systems and their prediction. **The total of TRMM-related research papers now numbers well over 600**. The complete list can be found at http://trmm.gsfc.nasa.gov.

TRMM products are used extensively by the research and applications communities as indicated by usage statistics from the Goddard DAAC. For the annual average over the life of TRMM, the total volume for data distributed was 6.7 times greater than the volume ingested into the archive. Adjusted to remove greater than usual volumes ingested due to reprocessing, the ratio of distribution to ingest becomes greater than 9 to 1. Level 3 products during the life of the mission enjoy an annual average volume distribution of 25.9 times greater than the volume ingested. **These data use ratios for TRMM are some of the highest of data sets residing at the Goddard DAAC**. In addition, since launch, the number of users requesting TRMM data has gone up every year, as the significance of TRMM data was realized by scientists and, more recently by applications researchers.

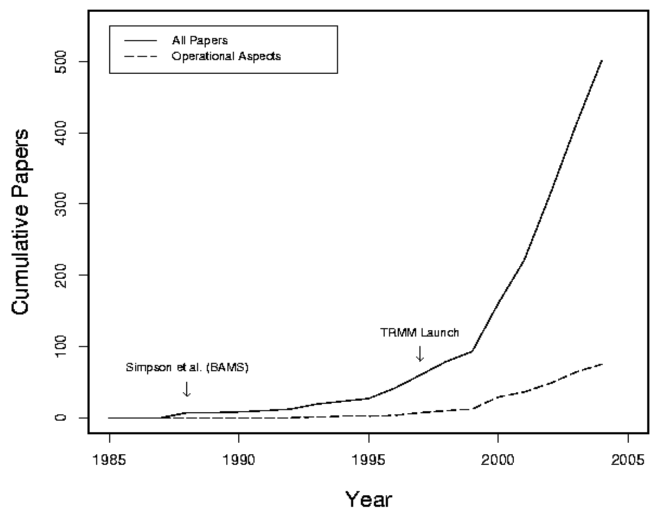

Fig. 2. Evidence of a rapidly growing body of refereed publications directly related to the Tropical Rainfall Measuring Mission. The data are obtained by searching the Institute for Scientific Information's Science Citation Index for papers that mention TRMM either in the title, abstract, or keywords. Papers dealing with operational aspects are based on terms such as "real-time," "operational," and "assimilation." Simpson et al. (BAMS) = Simpson et al. 1998. SOURCE: Matthias Steiner, Princeton University.

A summary of TRMM's scientific contributions in various categories is given in the following sub-sections. TRMM's original science goals have been met and many additional contributions have been made, beyond what was originally expected.

2.1 Climate-related research

Rainfall climatology. TRMM's new knowledge on rain distribution across the tropics has lead to **a benchmark seven-year rain climatology (Fig. 3), narrowing considerably the range of uncertainty in previous space-based rainfall estimates (Adler et al. 2003; Nesbitt et al. 2004)**, and to the unique monitoring of rainfall variations related to ENSO. The TRMM surface rainfall retrievals from the multiple instruments and algorithms are converging to become the standard for improving long-term climatologies and for comparison with climate models. The new Version 6 products now being produced and re-processed reduce the range of mean climatological results even further and will be used calibrate the 25+ year record of the community Global Precipitation Climatology Project (GPCP) of the WCRP.

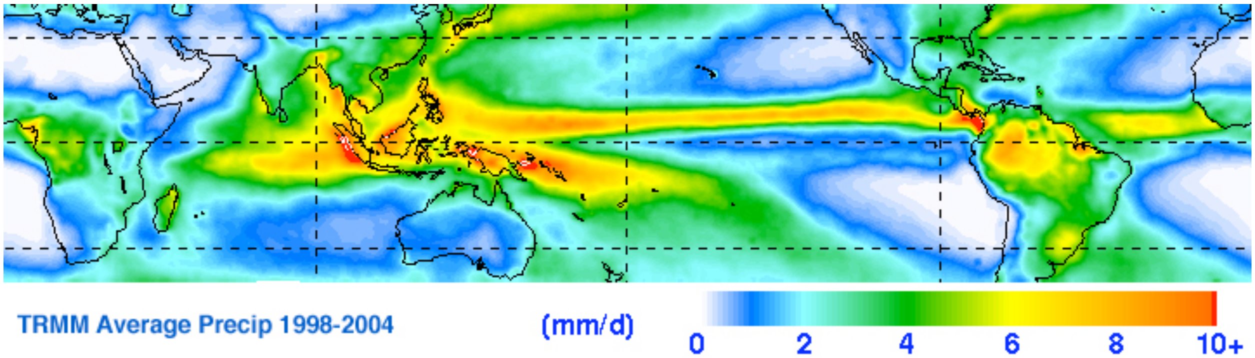

Fig. 3. Seven-year climatology of surface precipitation from TRMM Version 5 3B-43 multi-satellite product combined with gauge information.

<u>Diurnal cycle.</u> TRMM has allowed the **heretofore-impossible quantification the diurnal cycle of precipitation and convective intensity over land and ocean tropics-wide (e.g., Nesbitt and Zipser 2003) through the use of the PR.** This analysis shows the stark differences in the diurnal cycle of rainfall and convective intensity over land and ocean areas by different types of systems. Over the oceans (Fig. 4), the diurnal cycle of rainfall has small amplitude, with the maximum contribution to rainfall coming from Mesoscale Convective Systems (MCSs) in the early morning. This increased contribution is due to an increased number of MCSs in the nighttime hours, not increasing MCS areas or conditional rain rates, in agreement with previous works. Land areas have a much larger rainfall cycle than over the ocean, with a marked minimum in the midmorning hours and a maximum in the afternoon, slowly decreasing through midnight. MCS rainfall peaks about 6 hours later than non-MCS storm (WI [with ice] and NI [no ice] categories in the figure) rainfall over tropical land regions. The TRMM rainfall diurnal cycle been used to directly evaluate and improve climate models representation of convection and the diurnal cycle (e.g. Lin et al. 2000), however an detailed evaluation of climate models closer to their grid resolution will require a longer time sample from TRMM through a mission extension.

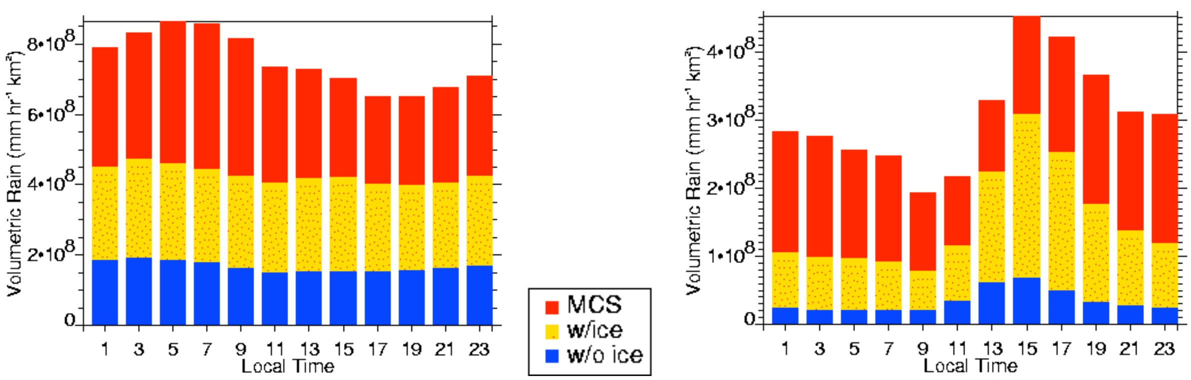

Fig. 4 Diurnal variation of rainfall by type of convective system over ocean (left panel) and over land (right panel).

<u>Convective/stratiform climatology.</u> The radar aboard the TRMM satellite has allowed **tropics-wide mapping of rainfall separated into its two main types, convective and stratiform, for the first time, with stratiform making up 45% of the total rain volume (Schumacher and Houze 2003).** This separation largely determines the vertical structure of latent heating associated with tropical precipitating systems and the corresponding large-scale atmospheric response (Schumacher et al. 2004). For example, the percent of rain that is stratiform significantly increases in the central and eastern Pacific during El Nino. The shift in overall precipitation to this region, along with the increase in the percent of rain that is stratiform dramatically changes upper level wind patterns, with effects seen into the mid-latitudes.

<u>Profiles of latent heating.</u> **TRMM products have provided the first comprehensive estimates of how rainfall is directly related to latent heat release in the atmosphere, and how that heating is distributed in the vertical,** a key characteristic in understanding the impact of tropical rainfall on the general circulation of the atmosphere.

Based on hydrometeor vertical structure information from PR and TMI and cloud model-based information TRMM scientists have derived climatologies of latent heating profiles (Olson et al. 1999; Tao et al. 2004) for analysis and comparison with global models.

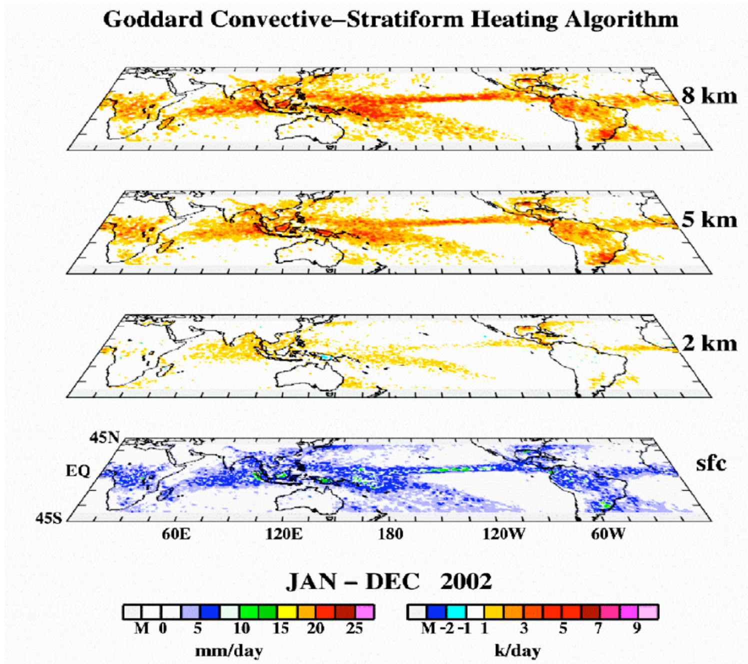

Fig. 5 Latent heating as a function of altitude for 2002 based on CSH algorithm.

Lightning climatology. The use of the lightning sensor, LIS, in conjunction with rain information has lead to a **detailed global mapping of lightning distribution, quantifying the lightning/convection relation for land and ocean** (Boccippio et al. 2000; Petersen and Rutledge, 2001; Toracinta et al. 2002; DelGenio and Kavari, 2002). During the 1997-98 ENSO there was a 50% increase in the number of days with lightning over the Gulf of Mexico and China Sea, owing to an increase in cyclogenesis and synoptic scale frontal passages (Goodman et al. 2000). Storms over Indonesia were more intense, producing more frequent lightning and having greater vertical development with accompanying deeper zones of ice phase precipitation, as observed by the PR and LIS (Hamid et al. 2001).

Improved climate simulations. **Assimilation of TRMM and other satellite precipitation information has led to improved simulations of the hydrologic cycle and climate characteristics and representation of convective systems, including simulations of the MJO (Hou et al. 2001).** In addition, several global atmospheric models use a prognostic cumulus kinetic energy (CKE), in which a parameter is used to relate the CKE to the cumulus mass flux. This parameter is expected to vary with cloud depth, mean shear, and the level of convective activity, but early work used a single constant value. Validation against TRMM, ERBE, and ISCCP data showed that this single-value approach cannot yield realistic simulations of both the diurnal cycle and the monthly mean climate states. This finding motivated the development of an improved parameterization that takes into account the effects of cloud depth, mean shear, and the vigor of convection (Lin et al. 2000). TRMM TMI, LIS, and CERES data have also been used to create a library of convective storm hydrologic properties that can be used to address cloud parameterization and feedback questions (Del Genio and Kovari, 2002) in global models. Results indicate behavior intermediate to that required by the "thermostat" and "adaptive iris" hypotheses of tropical climate regulation. A parameterization of convective detrainment-precipitation partitioning based on the observed TRMM behavior has been implemented in a GCM and found to imply a nearly neutral cloud feedback (Del Genio et al. 2005). TRMM data have also been used by Lau and Wu (2005) to validate GCM results using various autoconversion rates, with results clearly indicating the need for a more sophisticated parameterization approach taking into account various types of rainfall (convective, stratiform, etc.).

Impact of cities on rainfall climatologies. **TRMM PR data have been used to identify rainfall anomalies possibly associated with the urban environments of Atlanta and other U.S. cities (Shepherd et al. 2002**; Shepherd and Burian, 2003) that may be related to the urban heat island, variations in roughness or aerosols. This work is important because it confirmed TRMM's ability to identify convective-to-regional scale rainfall signatures and place them in the context of natural and anthropogenic forcing at regional to climate scales.

2.2 Convective Systems and Tropical Cyclones

Convective systems characteristics. TRMM PR, TMI and LIS data provided the information for **the first definitive climatology of the distribution of convective system characteristics from horizontal size, depth, extreme events,** etc. and how these characteristics are distributed as a function of geography, orography, time of day, etc. (Nesbitt et al. 2000). Regional differences in the vertical structure of convection (as determined by the PR) and the relationship with lightning and thermodynamic structure has been shown for the first time globally (Petersen and Rutledge 2002), and regionally over areas like the Amazon Basin (Petersen et al. 2002).

Aerosol-precipitation relationships. The unique combination of TMI, PR and VIRS data has allowed for critical observations to be made as to the relation between aerosols (including pollution) and rainfall. While VIRS data has helped to establish particle size information from cloud tops, TMI has defined liquid water content over oceans and the PR has noted the occurrence of rainfall in a combination that has led to **conclusions that aerosols in general, and pollution in particular, tend to decrease rainfall by limiting the number of larger drops (Rosenfeld 1999, 2000).**

Tropical cyclone rainfall characteristics. **TRMM TMI and PR data have been used to establish for the first time key characteristics of the distribution and variation of rainfall in tropical cyclones as a function of intensity, basin, stage of development, and environmental conditions (shear, etc.) (Cecil et al. 2002, Lonfat et al. 2004).** TRMM data are also being used to validate mesoscale models of simulated hurricanes (Braun 2004) and have been used to clearly establish a link between the appearance of deep convective cores in the eyewall region and subsequent rapid deeping of the storm (Kelley et al. 2004).

2.3 Measurement advances

Improvement of algorithms. Comparison of TMI and PR algorithms has led to **increased understanding of differences between, and therefore improvements to these retrievals and those for all passive microwave sensors** (Nesbitt et al. 2004). For example, time-dependent regional biases in satellite rainfall estimates have been shown to have significant implications for some climate applications such as the variability in tropical mean rainfall associated with ENSO. Differences between rainfall estimates from the active radar and passive microwave sensors on board TRMM have been used to identify several of the physical mechanisms leading to these regional biases. Berg et al. (2005) determined that errors in the estimated height of the freezing level used by many passive microwave rainfall retrieval algorithms are highly correlated with total column water vapor.

Combined instrument algorithm. The **first active-passive rain algorithm applied to satellite data** was developed for TRMM and has been applied since launch (Haddad et al. 1997). In relation to the PR and TMI separate algorithms the trio have been used to isolate differences and the physical basis for those differences. This has allowed the combined PR/TMI algorithm to mature during TRMM's lifetime. The combined algorithm has been used as the calibrating information in some multi-satellite analyses.

Multi-satellite analyses. With the TRMM satellite producing the best instantaneous rain estimates those estimates have been used to calibrate or adjust rain estimates from other satellites to provide analyses at higher time resolution than available from one satellite (Adler et al. 2000). Since the beginning of TRMM such a multi-satellite standard product was produced (albeit a simple TRMM-calibrated geosynchronous IR estimate at daily resolution). Recently, **new products are providing a 3-hr standard TRMM Multi-satellite Precipitation Analysis (MPA) product (Huffman et al. 2005) and other novel approaches to combine satellite rain information (Joyce et al. 2004).** The TRMM multi-satellite rain products are now being used, for example, to validate model characteristics of storms (Bauer and Del Genio, 2005) showing that the models produce generally realistic rainfall rates for mid-latitude storms, but with a pattern that underestimates precipitation east of the surface low in the strongest storms, which highlights potential inadequacies in the parameterization of mixed phase processes in the warm front region.

Rainfall assimilation. Unlike observations in clear-sky regions, rainfall data are difficult to assimilate because rain estimates from forecast models can have large biases. For a given analysis system, procedures must be developed to use rainfall data effectively. **TRMM has provided major impetus for the data assimilation community to explore innovative approaches to use rainfall data to improve atmospheric analyses and forecasts**. These new techniques range from variational rainfall assimilation using the model as a weak constraint (Hou et al. 2000) to super-ensemble forecasting techniques (Krishnamurti et al. 2001). The TRMM PR provided a key reference for estimating the uncertainty in radiometer-based rain retrievals. This information gives crucial inputs for variational assimilation of TMI rain rates (Bauer et al. 2002). TRMM research has provided clear demonstrations of the benefits of rainfall assimilation in a wide range of situations (Hou et al. 2001, Pu et al. 2002, Marecal et al. 2003, Aonashi et al. 2004).

2.4 Applied research

Hydrological applications. **TRMM-based multi-satellite data are being used as input into hydrological models, including LDAS systems, to better understand land-atmosphere interactions on scales of days to years (Rodell et al. 2004) and study variations in river runoff (Fekete et al. 2004).** These same data are also being used by USAID/NOAA/USGS to monitor crops in Central America and elsewhere, and as input into river forecast models in South Asia and other locations (Tokar [USAID] personal communication). Analysis of TRMM Precipitation Radar (PR) data along the Himalayas suggests orographic precipitation processes include cells of localized shallow convection embedded in bands of stratiform rainfall from the foothills up to 5,000 m (Barros et al. 2004) with the diurnal cycle of rainfall in the central Himalayas exhibiting nocturnal maxima during the monsoon (Barros et al. 2004). This late night/early morning rainfall maximum routinely causes flash floods in headwater streams everywhere along the Himalayan range.

Sea surface temperatures. With its 10 GHz channel on TMI, TRMM observations produced the **first SST data through clouds (Wentz, 2000).** These data have been used for numerous applications including for climate monitoring (Stammer et al. 2003, Reynolds et al. 2004) and the identification of cold wakes behind tropical cyclones.

2.5 Operational use of TRMM data

Early in the TRMM mission the TRMM data system (TSDIS) began to produce **real-time TRMM products** in a "best effort" mode. Numerous users requested through NASA HQ access to the real-time data. Other organizations, most notably NRL-Monterey, produced value-added operational TRMM products for their users. The end result has been an enormous use of TRMM data for operational forecasting, applied science and real-time research. The recent National Academy report describes numerous operational uses of TRMM data in he U.S. and internationally. The main uses of real-time TRMM data will be summarized in this sub-section.

Monitoring of tropical cyclones. TRMM data (primarily TMI data) are used by both NOAA (National Hurricane Center [NHC]) and DoD (Joint Typhoon Warning Center [JTWC]) in the U.S. and tropical cyclone centers in Japan, India, Australia, New Zealand, etc. for detecting location and intensity of tropical cyclones. **In 2004 more than 600 tropical cyclone fixes were made using TRMM by these agencies.** Because of TRMM's finer spatial resolution (compared to SSM/I) these fixes are usually considered among the best (most accurate) of satellite-based locations. In addition, TRMM's orbit (always in the tropics) provides data at different times than the sun-synchronous microwave instruments with its best sampling in the cyclone-important 10-37° latitude bands. TRMM data are also used (often in time histories with other satellite data) to detect changes in convection, eyewall formation and other features related to intensity change. TRMM data are frequently mentioned in warning center discussions.

Rainfall monitoring. Near real-time availability of TRMM-based multi-satellite estimations is being used by various entities interested in detecting floods in the U.S., but especially overseas where conventional information is lacking. NOAA NESDIS uses TRMM data as part of its Tropical Rainfall Potential (TRaP) program to estimate flood potential in hurricanes. **NASA's TRMM-based Multi-satellite Precipitation Analysis (MPA) [Figs. 6 & 7] is used by numerous groups and countries globally to detect floods and monitor rain for agricultural uses.** NRL-Monterey and NOAA/NCEP use TRMM data as a key part of their multi-satellite rain estimates. TRMM data are key to the success of these efforts because of its accuracy (including the use of PR data) and the significant sampling by TRMM in the tropics.

Numerical weather prediction. NCEP has been assimilating TRMM data into its global numerical weather prediction system since October 2001. Although the effect of including TMI on NCEP model forecast skill scores is small, there is evidence of modest improvements. JMA and the European Centre for Medium-Range Weather Forecasts (ECMWF) have led the way in using TRMM data in numerical weather prediction. **JMA is assimilating TMI observations into its global model and ECMWF has conducted a series of near real-time experiments with its 4-DVAR operational forecast system and plans to go fully operational with the TRMM data assimilation pending the decision to extend the TRMM mission.** ECMWF plans to use PR data to independently determine the error characteristics of input rainfall information from all satellite microwave sensors. Florida State University (FSU) has also had significant success in assimilation of TRMM data into their models, which are key elements of their Super Ensemble approach. The ensemble is trained on satellite precipitation data, including the high quality TRMM estimates.

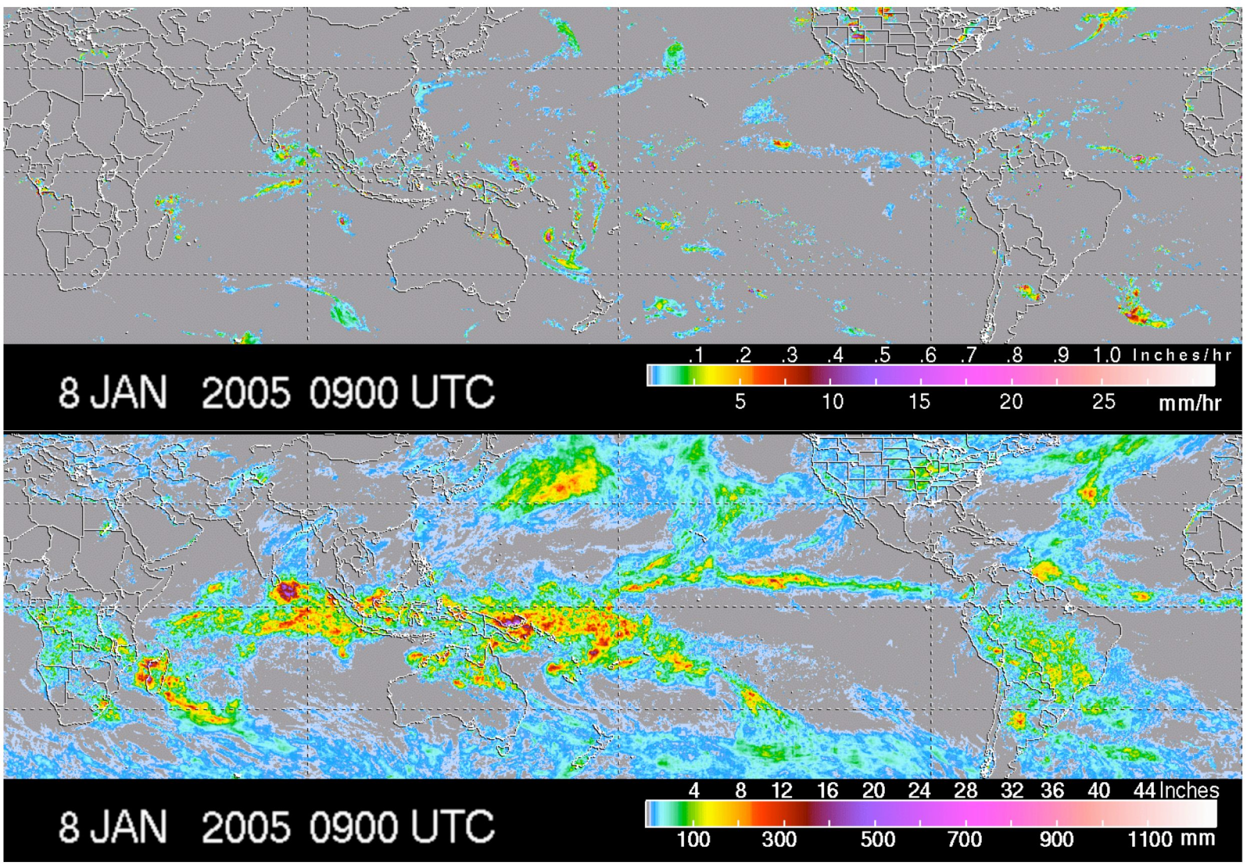

Fig. 6 & 7. Example of TRMM MPA instantaneous rain rate map (top panel) and seven day accumulation (bottom panel).

Air Traffic advisories. **LIS data are provided directly to the NOAA/NCEP Aviation Weather Center and also made available to Forecast Offices to identify (oceanic, in particular) convective weather hazards.** AWC forecasters responsible for convective and international SIGMETs (significant meteorological advisories) overlay LIS data with conventional visible and infrared imagery to better understand which convective cells have increased likelihood of turbulence.

3. SCIENCE WITH AN EXTENDED TRMM MISSION

The overall science objective of an extended TRMM mission is *to determine the time and space varying characteristics of tropical rainfall, hydrometeor structure and associated latent heating and how these characteristics are related to variations in the global water and energy cycles.* This TRMM goal is at the heart of NASA's Earth Science strategy and the answering of key science questions, primarily for the Water and Energy Cycle focus area, i.e., *"How are global precipitation, evaporation and the water cycle changing?"* and *"How will water and energy cycle dynamics change in the future?"* Having a long, accurate record of quasi-global precipitation characteristics is critical to achieving NASA Earth Science goals. Extension of TRMM for the next five years will provide that information and science to NASA and the world research community.

NASA Strategic Science Questions	TRMM Contributions to NASA Strategic Science Questions in the Next 5 years	Relevant Applied Science Areas
*How are **global precipitation**, evaporation, and the **water cycle** changing? **(variability)***	-Improved climatology of precipitation characteristics (e.g., diurnal variations, vertical structure, extremes) at finer resolutions -Diagnosing/testing of inter-decadal change and trend-related processes requiring detection of subtle changes in rain characteristics	Water Management, Agricultural Efficiency
*What are the effects of clouds and surface **hydrologic processes** on Earth's climate?* *How do ecosystems, land cover, and biogeochemical cycles respond to and affect global change?* *How do atmospheric trace constituents respond to and affect global environmental change?* ***(response)***	-Refined latent heating as a function of altitude (key climate system driver) -Assessment of impact of humans (e.g. cities and aerosols) on rainfall climatologies and precipitation processes -Robust convective systems characteristics (space, time, cloud type) and lightning characteristics -Hydrological applications over land (testing TRMM data in land data assimilation systems, basin scale assessments, and budget closure estimates)	Water Management, Agricultural Efficiency, Public Health, Coastal Management, Air Quality
*How are variations in local weather**, precipitation** and **water resources** related to global climate variation?* *What are consequences of land cover and land use change for human societies and sustainability of ecosystems?* ***(consequences)***	-Inter-annual variations of precipitation (e.g. longer, continuous TRMM data records will better characterize tropical seasonal-interannual climate variability in general and the El Niño-Southern Oscillation (ENSO) cycle in particular. -Assessment of impact of humans (e.g. cities and aerosols) on rainfall climatologies and precipitation processes	Water Management, Agricultural Efficiency, Public Health, Disaster Management, Coastal Management
How can weather forecast duration and reliability be improved? *How can predictions of climate variability and change be improved?* *How will **water cycle** dynamics change in the future?* ***(prediction)***	-Improving analysis and modeling of global water/energy cycle to advance weather/climate prediction capability (e.g. precipitation assimilation, process studies) -Continued improvement of weather forecasting, especially for monitoring/forecasting the intensity of tropical cyclones and the intensity of rainfall they yield. (NOAA, DoD, WMO Centers -Continued TRMM data stream would enable modelers and forecasters to continue to improve the overall numerical weather prediction process, (i.e., model development and validation, forecast initialization). This includes use of PR/TMI in calibrating similar data from other microwave sensors and contributes to improved global, as well as tropical, precipitation monitoring and prediction. (NOAA, JMA, ECMWF, USAID, USDA) -Continued sea surface temperatures in cloudy environments for hurricane forecasting	Water Management, Agricultural Efficiency, Public Health, Homeland Security, Energy Management, Disaster Management, Coastal Management, Air Quality, Aviation

Table 3. Matrix mapping for continued TRMM operations to key NASA Science Question and Applied Science Areas. The matrix is consistent with NASA 10 year outcome goals to: (1) enable seasonal precipitation forecasts at 10-100km resolution with greater than 75% accuracy, (2) balance global water and energy budgets to within 10%, (3) decrease hurricane landfall uncertainty from+/- 100 km in 3 day forecasts, (4) enable 7-10 day forecasts at 75% accuracy, (5) enable 10-year climate forecasts---Source: NASA Earth Science Research Plan-11/02/04 (Draft)

Table 3 relates expected, key TRMM contributions to each of the NASA Strategic Questions and also outlines to which applied science areas TRMM will contribute significantly. Obviously from the table, TRMM's contributions are critical to the NASA program and a loss of information from TRMM would create a distinct weakness in the observation of the water cycle and, therefore, NASA's research program.

NASA's research program and TRMM are also closely linked to the national scientific priorities identified by the U.S. Climate Change Science Program (CCSP) and to international coordination through the World Climate Research Programme (WCRP) - in particular the Global Energy and Water Experiment (GEWEX) and the Climate

Variability and Predictability (CLIVAR) program. In fact, it is noteworthy that it was only after TRMM had begun to fulfill its promise that the USGCRP focus (FY2000 Our Changing Planet) evolved to support the Water Cycle as a discreet program element. The prominence of the Water Cycle in the current Climate Change Science Plan and in the NASA science questions above is due, in large part, to the scientific success and longevity of TRMM. The TRMM results already described in Section 2, valuable though they are, are incomplete in many instances. For example, the seven-year climatology needs a larger database before we can have as much confidence in the precipitation variability as we now have in the mean values or regional statistics as confidently as we now have in global statistics. The definition of the tails of distributions, i.e., the definition of extremes, requires a longer data record. The human influences on precipitation are uncomfortably close to the noise level without a longer database. The tropical cyclone intensification hypotheses require additional cases for secure conclusions.

Specifically, extension of TRMM over the next five years will result in: 1) an improved climatology of precipitation characteristics, especially extremes; 2) improved diagnosis and closure of global (and regional) water cycles; 3) diagnosis and testing of inter-decadal and trend-related processes in the water cycle; 4) assessment of impact of humans (e.g., cities and aerosols) on rainfall characteristics and processes; 5) robust determination of convective system (including cyclonic storms) and lightning characteristics; 6) advances in hydrological applications overland (basin-scale assessments, water management); 7) improved modeling of the global water/energy cycles for weather/climate predictions; and 8) improved monitoring and forecasting of tropical cyclones, floods and other hazardous weather.

In the following sub-sections the basis for proposed research with an extended TRMM mission and the associated science questions are described.

3.1 Improved climatology of precipitation characteristics

Science Question 1: What is the climatological mean surface precipitation (zonal averages, 2.5° latitude bands) over ocean and land to within less than 5%?

Science Question 2: What is the fine (horizontal [~25 km]) scale climatology of precipitation characteristics (mean surface rain, diurnal cycle, vertical structure) on a monthly to seasonal basis?

The value of the relatively short (in climate terms) TRMM dataset for climate research increases rapidly with every year of added observations. The original motivation for TRMM and its low-earth, inclined orbit was to collect a benchmark climatology of tropical rainfall averages. This goal has been achieved to a large extent with 7-8 years of data, although a truly stable, high-resolution climatology of mean values requires a number of additional years. Precipitation is an episodic process with small-scale structure, and is therefore much more difficult to characterize than a continuous field such as temperature. The sampling problem becomes particularly severe when attempting to characterize such features as the seasonal cycle, the diurnal cycle, convective/stratiform separation and characterizing relatively rare, but important, extreme events. Evolution of TRMM algorithms and the convergence of results from the various instruments/algorithms (Adler et al. 2003a, Nesbitt et al. 2004) have led to greater confidence in the mean zonal averages of surface rain over the ocean. The Version 6 products (see Fig. 8) currently being produced have reduced the range of estimates of tropical ocean mean to about 10%. However, away from Tropics-wide averages, on finer scales such as at the resolution of a climate model (~2.5°), the TRMM rainfall algorithms still disagree relatively by larger values (Nesbitt et al. 2004). Continued improvement of algorithms and exploration of algorithm differences over the proposal period will lead to further convergence. A comprehensive climatology of these characteristics must consider their variability in space by season with type of disturbance and with other factors, such as MJO phase, tropical cyclones, or types of mesoscale convective systems. The TRMM database must be extended to establish the stable statistics to define the characteristic features of the tropical hydroclimate.

The extension of TRMM would become even more valuable if it overlapped with the implementation of the GPM mission, thus providing a continuous climate time series beginning in late 1997. The improved definition of these long-term means is critical for closing the global and regional water budgets, for validation of climate models, and for benchmarking longer satellite-based precipitation analyses such as the Global Precipitation Climatology Project (GPCP) (Adler et al. 2003b).

TRMM will provide refined, benchmark climatologies providing of surface rain, diurnal cycle and vertical structure means for global and regional water cycle closure and validation of climate models.

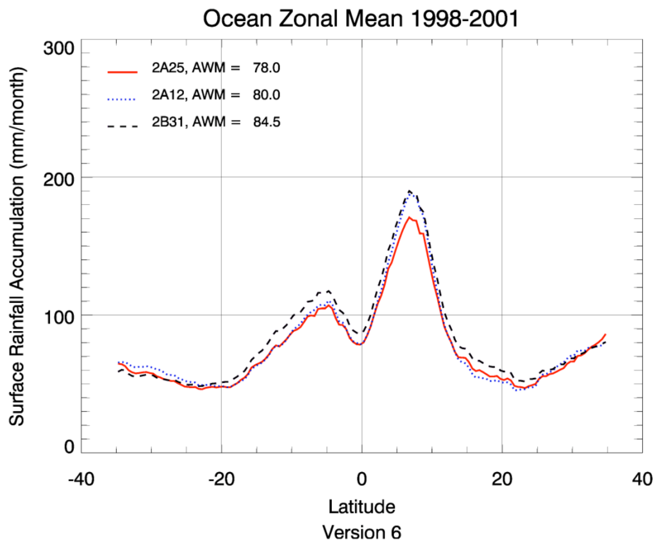

Fig. 8. Version 6 re-processing (currently underway) results for first four years of TRMM showing latitude profiles of mean ocean precipitation from the three main precipitation algorithms. Numbers are tropical means in mm/month.

3.2 Inter-annual variations of precipitation

Science Question 3: How do the characteristics of tropical precipitation (mean surface rain, hydrometeor structure, latent heating profiles, lightning activity, etc.) vary inter-annually in relation with ENSO and other phenomena?

Seasonally averaged precipitation in the tropics exhibits pronounced year-to-year variability. The more significant regional-scale variations are associated with large-scale interactions between the atmosphere and land and ocean surface conditions (e.g., soil moisture, sea surface temperature). However, rainfall is not simply a passive response to these interactions. Rather, through the release of latent heat it plays a major role in the dynamics of the interactions. The effects of regional-scale latent heating propagate throughout the tropics and into the extratropics (through teleconnections) where the remote response results in significant climate variability. Consequently a full description and understanding of interannual rainfall variability in the tropics requires both a quantitative description of rainfall anomalies and a diagnostic understanding of the role of rainfall in the coupled processes of the Earth-ocean-atmosphere climate system.

The most extreme and widespread year-to-year variations in tropical rainfall are associated with the El Niño-Southern Oscillation (ENSO) phenomenon. Climate models have difficulty in realistically simulating the ENSO cycle and its global response. One of several likely reasons for this is an inadequate model representation of the rainfall processes. TRMM provides a reliable quantification of the evolving rainfall field and crucial information on latent heating profiles. The seven-year TRMM record that now exists includes the later stages of the major 1997-1998 El Niño as well as the weak 2002-2003 event. The differences between these two events illustrate their variability in intensity and character from event to event. While these two realizations are useful for preliminary studies, they are insufficient for characterization of the hydroclimatic aspects of the ENSO and other inter-annual variations. Since El Niño recurs at irregular integrals of two to seven years, there is a high probability of one or more additional El Niño occurrences between 2005 and 2010. Continuous TRMM observations from 1997 into the Global Precipitation Measurement era would provide a unique and valuable continuous record for characterization of the ENSO cycle.

Extension of TRMM will better define ENSO-related (and other) inter-annual variations in precipitation characteristics for increased understanding and testing of climate simulations and seasonal-to-annual forecasts.

3.3 Diagnosing/testing of inter-decadal changes and trend-related processes

Science Question 4: What is our level of confidence in variations (inter-annual and inter-decadal) of large area precipitation means noted in long-term (~25 year) data sets.

Science Question 5: What is the relation between spatially integrated tropical precipitation and surface temperature on inter-annual time scales, and how is that related to possible global warming/water cycle acceleration scenarios?

Even with a mission extension of 4-7 years TRMM's potential total length of record, by itself, is obviously limited in assessing precipitation changes over inter-decadal periods or longer. On the other hand, the TRMM data could be the start of a long-term record of radar/microwave radiometer data if temporally linked to GPM in the future. However, even a modest extension of the TRMM record will be useful in terms of helping to evaluate longer time period changes. For example, the shorter, but independent, 7-year TRMM record is being used to assess the accuracy of variations and trends in the 25-year GPCP precipitation analysis by examining the overlapping period (1998-present). Especially important is the use of the PR information to confirm or question inter-annual to inter-decadal variations evident in the passive microwave record, which extends back to the middle of 1987 using the SSM/I instrument.

In addition, quantifying the associated *net integrated changes* to water and heat balance over the entire tropical oceanic or land sectors remain an observational challenge. While ENSO events are clearly not a climate change phenomena, they are important perturbations to the tropical and global energy and water balance and are accessible science "targets" for TRMM. Earlier pre-TRMM investigations (Soden 2000, Robertson et al. 2001) have suggested that, at least over tropical oceans, passive microwave emission and scattering techniques both yield positive correlations with SST. On the other hand, Su and Neelin (2003) have used a tropical climate model of intermediate complexity to argue that a poor correlation exists between tropical average SST anomalies and precipitation anomalies. It is essential to document these integrated responses, to understand the physical processes at play, and to validate our ability to model these large climate variability signals. TRMM is still in the process of providing resolution to this issue. Robertson et al. (2003) have noted remarkable differences between the Version 5 TRMM PR and 2A12 and 3A11 precipitation algorithms, the latter two being based solely on measurements from the TMI. This behavior is illustrated in Fig. 9 (left panel). The two TRMM TMI algorithms support previous passive microwave findings of positive ocean-averaged precipitation / SST anomaly correlations. However, the TRMM PR time series is notably different, exhibiting correlations with the TMI algorithms of only 0.12.

Comparison of attenuation versus reflectivity information from the PR (Robertson et al. 2003) suggests that uncertainties in microphysical assumptions regarding drop size distributions (DSDs) needed for the primary TRMM algorithm (2A25) are still problematic for climate applications. Supporting evidence for the sensitivity of PR rainfall to attenuation correction and the associated DSDs also comes from considering precipitation rates in rain systems above the freezing level (5 to 6 km) where attenuation is much weaker (Fig 10, right panel.) The interannual behavior at 6 km is strikingly different from that at 2 and 4 km and agrees more with the TMI passive algorithms (see left panel). Precipitation anomalies above 10% are present in early 1998 and are persistently near minus ~ 5% during 1999 and early 2000. Early results indicate that the new TRMM V6 algorithms will narrow these uncertainties substantially, but will not eliminate them. Every year that the TRMM mission can be extended helps reduce sampling error in isolating not only ENSO events, but also in narrowing uncertainties in precipitation trends and low frequency behavior. In turn, this helps narrow uncertainties in evaporation and moisture transport in closing the water budget.

TRMM will provide a lengthened record of independent surface rain and vertical structure information necessary to diagnose critical, subtle variations and changes related to climate change scenarios.

3.4 Improving analysis and modeling of global water/energy cycle to advance weather/climate prediction capability

Science Question 6: What are the key processes linking tropical precipitation systems to monsoon, intraseasonal oscillation, and ENSO dynamics in producing climate variations on the global water and energy cycles?

Science Question 7: How do we devise optimal data assimilation procedures to maximize the information content from space radar and radiometer precipitation measurements to improve climate analysis and numerical weather prediction?

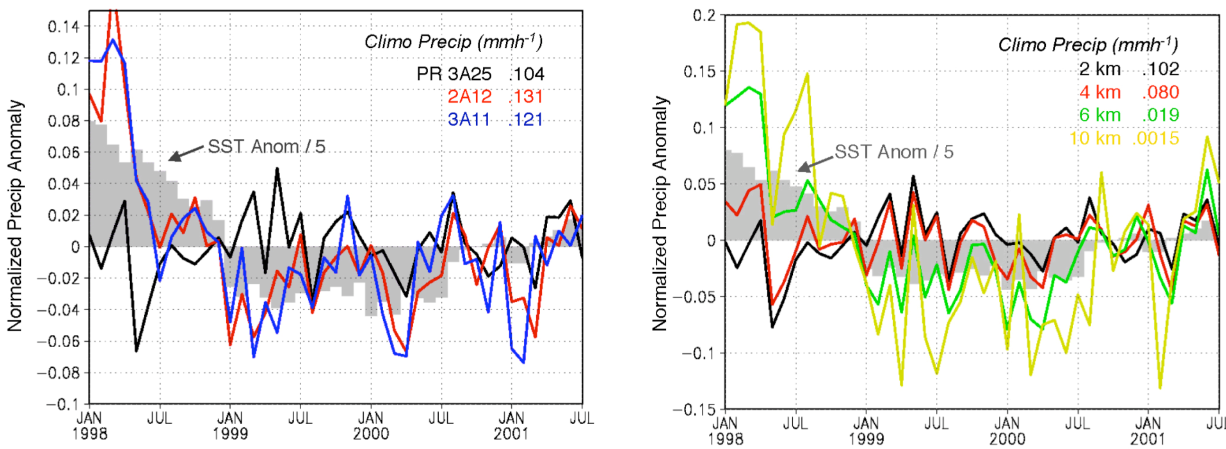

Fig. 9 & 10. Time history of TRMM surface rain and SST from January 1998 (El Nino) onward showing radar-based value differing from radiometer results (left panel). Right panel shows radar information at higher levels (4, 6 km) is similar to radiometer-based time history. (Robertson et al. 2003).

Data assimilation is a statistical estimation procedure that integrates observations with model information to provide a physically consistent estimate (i.e. analysis) of the global water and energy cycles. But at the present time global analyses have considerable uncertainties in basic hydrological variables such as precipitation and evaporation (WCRP 1998), especially in the tropics.

Since the launch of TRMM there has been a growing body of evidence showing the benefit of assimilating rain rates from passive microwave radiometers for improving both analyses and forecasts provided by mesoscale and global numerical weather prediction systems (Chang et al. 2001, Hou et al. 2001, 2004, Pu et al. 2002, Kato et al. 2003, Marecal et al. 2002, Aonashi et al. 2004). In addition, Krishnamurti et al. (2001) have demonstrated the value of microwave rainfall data in multi-analysis and multimodel superensembles for achieving greater forecast skills than any of the ensemble members. With its unique low-inclination, non-sun-synchronous orbit, TRMM provides crucial rainfall measurements filling the gaps between the current fleet of polar-orbiting passive radiometers during a typically 6-12h data assimilation window. The additional sampling by TRMM yields more accurate climate analyses in terms of the atmospheric circulation, moisture distributions, and cloud-radiation energy fluxes in the tropics (Hou et al. 2001). Rainfall assimilation provides global analyses that are dynamically consistent with observed precipitation, which are crucial for breaking a major roadblock in understanding the interplay between tropical convective systems, monsoons, and MJO’s on intraseasonal time scales, and the global impact of ENSO variability on interannual time scales (see Fig. 11 for MJO improved simulation result). The improved analyses are also capable of upgrading weather forecasting skills, leading to better predictions of severe storms and extreme weather events in the tropics.

The data assimilation and NWP community is only in the early stages on the learning curve to develop techniques to make effective use of space-base rainfall measurements. For instance, research is just underway to examine ways to assimilate TRMM/PR rain rates, reflectivity profiles, and the associated latent heating products. The launch of CloudSat and CALIPSO in 2005 will provide a unique opportunity to test value of combined use of cloud and rain profile information to improve climate analyses and forecasting skills. But the anticipated progress in this area at operational NWP centers is contingent upon having TRMM data in the near real-time observation data stream. In the U.S., the continued TRMM real-time data availability will provide crucial impetus for the NASA/NOAA/DOD Joint Center for Satellite Data Assimilation (JCSDA) to develop cloud/precipitation assimilation algorithms for operational weather forecasting. Moreover, as NWP agencies experiment with radiance assimilation in rainy regions in the coming years, the TRMM PR will have a critical role in precipitation forecast validation.

Continuation of TRMM will enable a 10-plus year analysis of the complete global water and energy cycle through the use of global data assimilation systems and the assimilation of TRMM precipitation information.

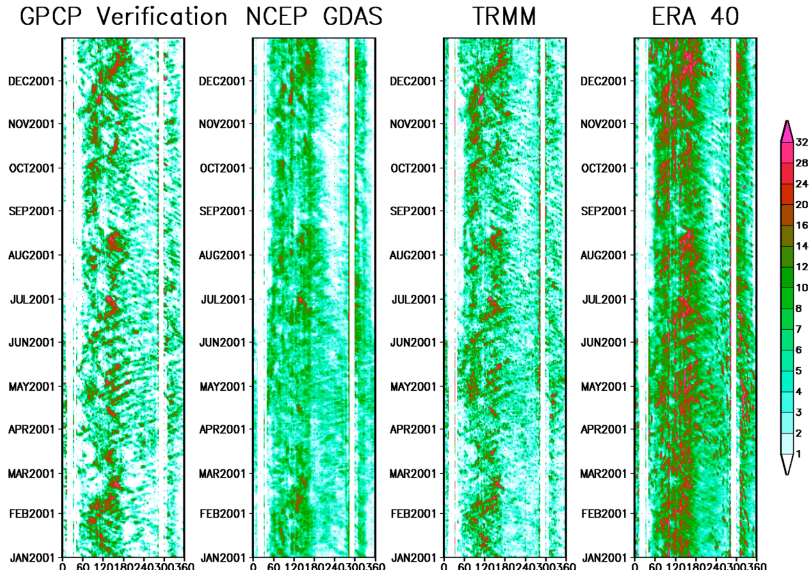

Fig. 11. Comparison of Madden-Julian Oscillation (MJO) signals in tropical oceanic precipitation (10N-10S) between GPCP satellite-gauge estimates and global analyses from the operational NCEP/GDAS, the NASA/TRMM re-analysis and ECMWF re-analysis (ERA-40) for 2001. The TRMM re-analysis, which assimilates 6h TMI and SSM/I surface rain data, is much better at capturing the intensity and propagation of tropical rain systems than other analyses that do not assimilate satellite rainfall data.

3.5 Characteristics of convective systems

Science Question 8. What is the global distribution of intense convective storms and severe weather, and can their regional distributions and time variations be explained from dynamical, microphysical and/or other factors?

Science Question 9. What are the space and time distributions of extremes in convective intensity, surface rainfall rate and lightning and how are they related to large-scale seasonal, inter-annual and inter-decadal variations?

The seven years of TRMM data have been extremely important in determining numerous characteristics of convective systems and how they vary regionally, seasonally, and under different environments. However, the limited time record hampers close examination of these characteristics and is insufficient to look at others. Climate consists not only of long-term averages, but of deviations from those averages, and in many cases it is precisely those more extreme deviations (especially when precipitation is concerned) that have the greatest impacts on humans. For example, the TRMM PR data are unique in their ability to describe the incidence of extreme penetrations of convective storms into the stratosphere. The greater the penetration (or the greater the overshooting of the level of neutral buoyancy), the greater the convective vertical velocity, and the more likely that storm is to produce extremely severe weather. Thus, TRMM is uniquely capable of studying the incidence of extreme convection and severe weather over most of the planet. By definition, these events are infrequent, so definitive statistics of extremes require lengthy data records. The same holds true when trying to evaluate the regional rainfall contribution and diurnal cycle from relatively rare but hydrologically crucial Mesoscale Convective Systems (Nesbitt and Zipser, 2003), or when trying to evaluate how environmental characteristics (such as background thermodynamics or aerosols can affect precipitation processes and diurnal cycles in a given region (e.g., Petersen et al., 2002, Betts and Jakob 2002). The TRMM PR sampling of any given location is of order 15 times per month; so additional years of the database are required to make statistics on diurnal cycles, annual cycles, and regional details valuable.

A more fundamental research objective that requires the TRMM database of extremely strong storms is the mass exchange between troposphere and stratosphere. Pioneering research by Danielsen (1982, 1993) proposed the hypothesis that such intense storms control the water vapor distribution in the stratosphere by "freeze-drying" the ascending mass. Subsequent papers have proposed different mechanisms (e.g. Holton and Gettelman 2001, Hartmann et al. 2001). The TRMM data now show that the most extreme overshooting clouds are found over continents, notably Africa (Fig. 12). This is also the region on earth with the greatest mean annual flash density. These new results directly contradict conclusions from IR data, which favor the west Pacific and Indonesian regions studied by Danielsen and many others. While the dominance of such strong storms over Africa is probably secure, we have insufficient data to be able to define accurately the precise locations (the 5-degree box data are very noisy), the diurnal and seasonal cycles, and the environmental conditions that favor extreme rather than merely strong convection. The fact that the intense African convection may well be injecting the products of biomass burning and other pollutants into the stratosphere is potentially important to understanding global biogeochemical cycles. [If the alternative view prevails (that the west Pacific convection dominates), the air injected into the stratosphere would likely be very clean.]

Extension of TRMM will provide the data necessary for definition of statistics of occurrence of extreme convection and its role in troposphere-stratosphere exchange.

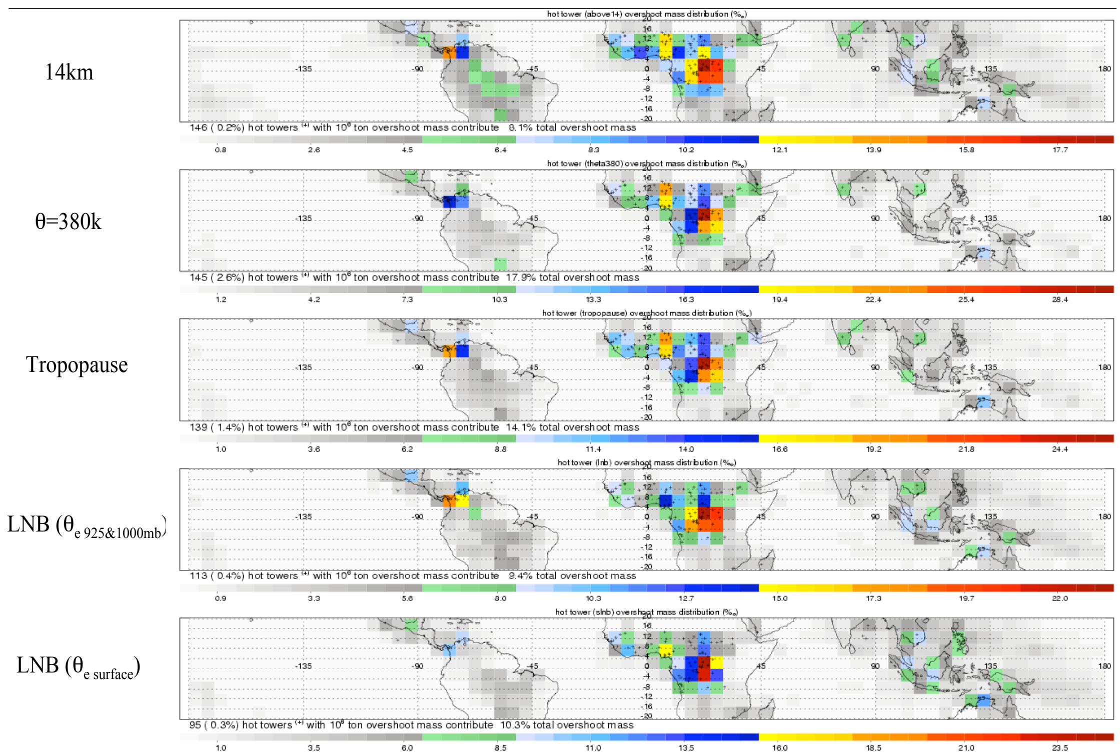

Figure 12. Fractional contribution (parts per thousand) of each 5-degree square to total mass of precipitating ice from hot towers in the tropical tropopause layer for 5 years of TRMM PR data. Five different reference levels are used, with average height ranging from 14,0 – 16.8 km. For any definition of reference level, the dominance of land over ocean, and of tropical Africa over South America and Indonesia is clear.

3.6 Tropical cyclone processes

Science Question 10: What are the primary physical processes relating inner core convection to tropical cyclone intensity change?

Science Question 11: What are the rainfall, convective structure and microphysical characteristics of tropical cyclones and how do they vary with storm strength, geographic location, and environmental conditions (e.g., shear)?

Data from TRMM have stimulated advances in tropical cyclone research and understanding. The PR is the only space-based method for quantifying the vertical structure of these convective systems - and it has already provided more data on the vertical structure of precipitation in tropical cyclones than a quarter century of aircraft penetrations into hurricanes in the Atlantic and the Caribbean. For example, the connection between convective bursts (exceptionally deep and energetic convective towers in the eyewall) and sudden intensification is a critical research topic. A study from a limited sample of storms (Kelley et al. 2004) suggests that when convective "hot towers" exceed 14.5 km height, there is an 80% probability that the storm will intensify. However, characterizing and understanding the relationship between these convective bursts and tropical cyclone variability will require a longer record than is currently available. Over the first six years of TRMM data, the TMI instrument passes within 750 km of storm centers during one of every eight orbits, whereas PR observes within 250 km of the center during one of every 25 orbits. The narrow swath of the PR and short-lived nature of convective bursts strongly argues for mission extension to increase sample sizes for statistical analyses.

Factors controlling the horizontal distribution of rainfall in tropical cyclones are also poorly understood, yet freshwater flooding accounts for the majority of tropical cyclone deaths. A published climatology of early TRMM data (Lonfat et al. 2004) is shedding light on the radial distribution of rainfall as a function of storm intensity, and how rainfall asymmetries are related to vertical wind shear. With improved accuracy of forecast track and storm propagation speed, rain accumulation forecasts have recently become operational based on these results. However, the relatively short TRMM record has not sampled a wide variety of extreme events. More hurricane seasons of TRMM data would allow researchers to reduce uncertainty in these statistics since more details of the many influences from intensity, location, track speed, and other factors on the rainfall could then be included.

The vertical structure information from the PR indicates the distribution of latent heat release in tropical cyclones. This information is used to verify the cloud and precipitation structure in mesoscale tropical cyclone models. Joint Hurricane Testbed projects relate the TRMM data to several of these models, such as those of Geophysical Fluid Dynamics Laboratory, the Eta vertical coordinate model, and the Global Forecast System (Marchuk et al. 2004). Further research with TRMM PR data will give a better understanding of the vertical structure of precipitation in tropical cyclones. In addition, the models need to be validated with high-resolution TRMM precipitation data. Whereas research aircraft radar can provide some data of similar resolution, a satellite-based system is required to validate the precipitation during all stages in the hurricane life cycle and in regions where research aircraft are not available.

Continuation of TRMM will provide improved understanding of tropical cyclone intensification processes through stable statistics of PR-based vertical structure and improved model simulations.

3.7 Hydrologic cycle over land

Science Question 12: How are hydrologic fluxes and states such as runoff, evapotranspiration, soil moisture, and groundwater recharge affected by changing precipitation patterns?

Science Question 13: Is the frequency of extreme hydrologic events such as droughts and floods changing?

TRMM provides the most advanced platform for satellite-based rainfall estimation over land due to the combination of active microwave (PR), with passive microwave (TMI), infrared (VIRS) and lightning imaging sensors (LIS). Accordingly, TRMM is a unique asset for studies of the hydrologic cycle over land, particularly since major fractions of the land area in key tropical river basins (e.g., the Amazon and Nile) contain few rain gauges. As such, the TRMM-PR is one of the most valuable instruments in space for analysis of the terrestrial hydrologic cycle, as it allows for determination and characterization of the errors and biases inherent to the other methods (IR, passive microwave, etc.) and provides results that can be extended to current and future (e.g. GPM) platforms. TRMM is also the key component of multi-satellite precipitation analyses, which are very important starting points for much land hydrologic work.

For example, a key unresolved science issue related to the hydrologic cycle over land is how changing precipitation patterns at multiple scales will translate into changes in hydrologic fluxes and states, such as runoff, evapotranspiration, soil moisture, and groundwater recharge. Recent analysis (Fekete et al. 2004) demonstrated a significant amplification of uncertainty in using precipitation fields from commonly applied global precipitation products (6 including TRMM) fields to determine spatially-distributed runoff, which ultimately is the source of renewable freshwater resources. Also, the global geography of runoff source areas shows nearly 20% of humankind with little or no access to renewable supply, a high degree of water scarcity, and economic hardship (Vörösmarty et al. 2005). Accurate assessment of renewable freshwater resources is critical to economic and social development and the entry point for making such estimates is accurate precipitation measurement. Understanding and predicting these changes is a key goal of the Global Land Data Assimilation System (GLDAS; Rodell et al. 2004), which uses TRMM-based multi-satellite data as input into several hydrological models.

As discussed above, extension of TRMM to 2010, or beyond, would almost double the record length and would undoubtedly result in major improvements in the comprehensiveness and robustness of a variety of hydroclimatic statistics, including their year-to-year variability. In addition to global water budgets, a key terrestrial hydrologic science question is whether, when and where the frequency of extreme events such as droughts and floods is changing. This question can only be evaluated with continuous, long-term, accurate estimates of precipitation over land. Continuation of TRMM is critical for the advancement of use of satellite precipitation information in land hydrology studies and applications.

Extension of TRMM will lead to improved global and regional simulation of land hydrologic processes through assimilation and resulting increased understanding and improved applications.

3.8 Impacts of humans on precipitation

Science Question 14: What is the quantitative aerosol-precipitation relation on a global or regional basis and the relative impact of pollution on those relations?

Science Question 15: How are the existence and strength of urban precipitation anomalies related to urban size, seasonal climate and aerosol environments?

Detecting the possible impact of human civilization on the precipitation component of the water cycle has been an unexpected research result of TRMM. Additional years of TRMM data would aid that definition and possibly even detect trends in that impact. The human impact research falls into two general areas, impact of pollution on precipitation in general and the impact of urban areas on precipitation patterns.

Several studies using combined TRMM PR-TMI-VIRS data have suggested that aerosols, both natural and anthropogenic, play a pivotal role in precipitation processes (Rosenfeld, 1999; Rosenfeld, 2000, Ramanathan et al. 2001; Givati and Rosenfeld 2004; Andreae et al. 2004). A great deal of work remains because most results (e.g. Rosenfeld 1999, 2000) suggest that aerosols reduce precipitation, while other results indicate that under proper conditions, aerosols may invigorate convection, leading to more lightning and more intense rainfall rates (Andrea et al. 2004). Berg et al. (2005) found evidence suggesting that high concentrations of sulfate aerosols over the East China Sea may be responsible for large amounts of cloud water in the cloud systems there, which are erroneously reported as rainfall by the TRMM TMI retrieval algorithm, whereas the PR results which show very little rain. The hypothesis is that the pollution from South China is affecting the precipitation off-shore through the increased aerosols favoring the liquid water remaining cloud water and droplets not growing to precipitation size. Further research (and additional data) are needed to better define these relations and even to possibly detect a change in that region over the TRMM era due to increased industrial activity during the last decade.

The second area of research is the use of TRMM information to link urban dynamic effects on precipitation related to urban heat island, enhanced roughness and convergence. Shepherd et al. (2002) explored the feasibility of using TRMM precipitation radar (PR) data to identify rainfall anomalies possibly associated with the urban environments of Atlanta, Dallas and other U.S. cities. Shepherd and Burian (2003) used PR data to confirm anomalies over and downwind of Houston, Texas. Shepherd (2005) demonstrated the use of TRMM-based multi-satellite precipitation analysis to extend their work to additional major global urban centers. This urban impact work is also starting to include the effect of urban aerosols.

The benefits of an extended TRMM mission for assessing human impacts on precipitation would be: (1) a longer sample record to determine if observed urban and aerosol signals truly reflect a climate change processes or local weather variability; (2) access to the TRMM precipitation radar is critical for direct measurement of precipitation in aerosol-laden or urban environments rather than less direct techniques; (3) the unique combination of instruments on TRMM allow for integrated urban-aerosol-precipitation studies to test emerging hypotheses; and (4) optimization of the TRMM-based MPA product to extend urban research to mid-latitude cities. As new satellite-based aerosol and cloud measurement capabilities become available in the next 5 years (e.g., CloudSat, Aura), it is optimal to have TRMM measurements available, particularly the PR data, until GPM launches to address the relative impacts of urban surfaces and aerosols on precipitation processes.

TRMM will provide an improved assessment of the impact of humans by increased air pollution and expansion of urban areas on climate change in the water cycle.

3.9 TRMM combined with new, unique observations

Science Question 16: What fraction of tropical precipitation occurs at rainrates below 0.5 mm/hr (PR threshold), and how does that fraction vary in space and time? [based on combination of TRMM PR and CloudSat radar data]

Science Question 17: How do microphysical (cloud, aerosol, precipitation) processes interact with mesoscale and larger dynamics in the initiation and evolution of tropical cyclones? [based on detailed field experiment aircraft observations and TRMM and other satellite overpasses]

Science Question 18: How does lightning frequency and distribution, and the associated variation in precipitation processes, affect the production, distribution, and variation of NO_x? [based on combination of TRMM, and Aura, data]

Extending TRMM for the next few years will allow for unique overlap data sets that will be highly useful in pursuing new science questions and adding to existing research endeavors.

The most obvious example of such a contribution is the combination of information from CloudSat (and the entire "A-Train") and TRMM. CloudSat will use radar (95 Ghz) to measure the vertical structure of clouds from space including some characteristics of precipitation. CloudSat will fly in formation with other satellites (including Aqua) referred to as the "A-Train." This constellation comes into formation with the launch of CloudSat and CALIPSO (with its cloud lidar) in mid-2005. Combining the observations of the A-Train with TRMM will provide an unprecedented view of clouds, aerosol, and precipitation. Because the TRMM and CloudSat mission satellites both carry radars, but with different and complementary wavelengths, the opportunity to have measurements at both radar frequencies simultaneously over a substantial amount of time will provide a basis for statistical comparison and cross-referencing. Such a combined dataset would yield a direct measure of the percentage of the light precipitation that has been below TRMM's measurement threshold. This is also important for GPM algorithm development, in particular through validation of these algorithms for higher-latitude precipitation. GPM will provide radar information at 14 and 35 GHz. TRMM information (especially the radar) will also add value to the A-Train observations of clouds and precipitation and to the effect of pollution and aerosols on precipitation and in combination with water vapor observations from the Microwave Limb Sounder (MLS) on Aqua to examine the role of detraining deep tropical convection in moistening the Tropopause Transition Layer (TTL).

The atmospheric chemistry community has been one of the largest consumers of archived LIS data sets. Lightning heats a channel to tremendous temperatures, and nitrogen oxides (NOx) are produced. The NOx eventually enhance tropospheric ozone concentrations through catalytic reactions, provided other chemical species are present. It is estimated that almost all of the NO_x over the oceans and 50–90% of NO_x emitted over some continental areas on a seasonal basis is attributable to lightning (Bond et al. 2002). One of the science objectives for the Tropospheric Emission Spectrometer (TES) on Aura is to examine the production of NO_x from lightning. Continuation of TRMM will allow for linkage to key information (Jeker et al. 2000; Zhang et al. 2000) provided by LIS.

As stated before, the combination of TRMM's TMI and PR with the microwave sensors on other current satellites provides many of the key elements of a GPM constellation concept. Data from the PR and TMI provide the rainfall reference point for the entire constellation thereby enhancing the data products from all constellation sensors. TMI has also served as a calibration standard for the other passive microwave sensors, because of its excellent, steady calibration and its inclined orbit, which provides numerous cross-overs with the polar orbiting sensors. In a similar way, the LIS provides calibration for the surface lightning networks, whose performance is affected by topography, conductivity, the state of the ionosphere, and other radio propagation effects.

Unique opportunities also exist for the TRMM mission to enhance atmospheric field campaigns over the next several years, including the Tropical Cloud Systems and Processes (TCSP) initiative in Summer 2005. TCSP will include the NASA ER-2 and NOAA aircraft, and the key emphasis of this experiment will be hurricane genesis and associated environmental processes, where TRMM observations will obviously be important. A second example of an upcoming field experiment where TRMM data is needed is the African Monsoon Multi-Disciplinary Analysis (AMMA), an international research project with a field campaign in 2006. AMMA seeks to better understand the variability of the West African monsoon and Atlantic tropical cyclone formation, especially the effect of the Saharan Air Layer (SAL) on cyclone formation. The TRMM data would be critical because of the uniqueness of having the PR co-located with the TMI to study SAL interaction with the tropical cyclones. The TRMM data would help separate physical processes by which the aerosol layer is affecting storm formation and intensification.

Continuation of TRMM will allow for new, unique joint data sets with Cloudsat, other satellites and field experiments to extend our knowledge of cloud, aerosol, precipitation and chemistry characteristics and interactions.

3.10 Applications and operational use of TRMM data

Science Question 19: What is the impact of TRMM data in the forecasting of position and intensity of tropical cyclones, and how does that vary with type of storm, ocean basin, etc.?

Science Question 20: What are the quantitative limitations for various applications of the accuracy and the time and space resolutions available from space observations of precipitation?

As indicated in section 2.5 of this document and confirmed by the NA conclusion on operational applications (see section 1.3), TRMM data have been effectively used in various applications and operational uses over the past seven years and clearly these uses will continue, be improved and new applied uses will be developed. In tropical cyclone monitoring and forecasting TRMM TMI will continue to provide ~600 location fixes per year at different times than available from polar-orbiting passive microwave instruments. PR data are available in real-time (same latency as TMI). In 2005 Goddard scientists, with advice from NRL and NHC personnel, are developing a real-time PR/TMI tropical cyclone product that will be available for forecasters (example in Fig. 13). It will show PR surface rainfall rates at full resolution (5 km) with TMI rainrates in the wider part of the swath to provide larger-scale information and context. Three-dimensional structure from the PR data over the storm will also be displayed for evaluation of radar echo strength, height, etc. Since accuracy of initial locations affects model forecasts of position, it can be assumed that TRMM observations of initial position are positively impacting forecasts. Models will also make improvements in assimilation of precipitation information for forecast improvement, so TRMM's impact should increase even beyond what has already been shown.

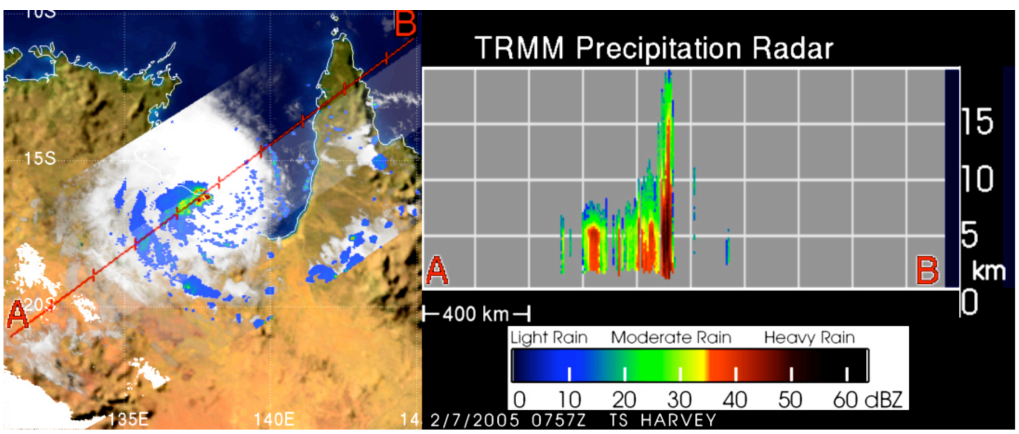

Fig. 13. Example of prototype real-time PR product for tropical cyclone monitoring and research. Example is for Tropical Cyclone Harvey in northern Australia in February 2005.

In addition, extension of TRMM will allow for the PR to be more widely used to calibrate ground-based radars (Bolen and Chandrasekar, 2003, Anagnostou et al. 2001), which will improve surface-based rainfall estimates in the USA and abroad.

Operational data products using TRMM data as the keystone in techniques using multiple satellites to analyze precipitation at high time resolution will continue to improve and the utilization of these data sets for various practical applications such as flood detection and forecasting, landslide detection, aviation hazards, crop moisture monitoring, soil moisture estimation will expand.

Continuation of TRMM will result in additional improvement in the monitoring and forecasting of tropical cyclones, floods and other hazardous weather.

<u>Technical Section</u>

4. TRMM MISSION STATUS

4.1 TRMM spacecraft status

The TRMM spacecraft is in excellent shape after seven years in orbit. In 2004 an independent technical assessment of extended life of the TRMM spacecraft was performed by the Mission Engineering and Systems Analysis Division (Code 590) of Goddard. The assessment was led by John J. Deily, the Associate Chief of the Division. NASA Headquarters was briefed on this subject by Deily on March 26, 2004. In particular, the following are noted from the presentation report:

Redundancy Assessment:
No credible single point failures
All credible faults have block or functional redundancy
Probability of TRMM's life being limited by radiation or Atomic Oxygen effects through 2010 – *very low;*
Probability of TRMM's life being limited by reaction wheel failures through 2010 – *very low*;
Probability of TRMM's life being limited by gyro failures through 2010 – *very low.*
Probability of critical hardware failure vs. time--*24 month failure probability <4%; Post-redundancy analysis results ~ 2x higher probability of failure once system is single-string due to 'most likely' first failure*

The most serious spacecraft problem affecting TRMM is with the Solar Array Drive Actuators (SADA). The two solar arrays are designed to track the sun. One array, the –Y side array, is always on the sun, or warm, side (TRMM does routine yaw maneuvers to keep one spacecraft side toward the sun). The –Y side SADA has operated at environmental temperatures beyond design limits since launch. In 2002 the –Y SADA briefly malfunctioned (did not fail) and it was decided to park the array (discontinue sun tracking) in the horizontal position to avoid the possibility of that array becoming stuck in a non-preferred position. This lack of sun tracking with the one solar array has led to slightly less available power, but sufficient power for nominal operations of all working instruments (CERES was powered down at this point). The +Y drive is operating well within temperature limits and is not expected to experience the same problems. "+Y SADA remains fully operational with no indication of problems" (Deily presentation).

In summary, in terms of TRMM mission extension impacting spacecraft systems, the *"change in risk is minimal."* (Deily presentation)

4.2 Status of TRMM instruments

<u>*Precipitation Radar (PR).*</u> **The PR is the first rain radar in space and will be the only rain radar in space until GPM**. Its key observation goals can be summarized as 1) providing three-dimensional structure of rainfall, particularly the vertical distribution and 2) obtaining high quality, quantitative rainfall measurements over land as well as over ocean. The PR was developed by the Japanese National Institute of Information and Communication Technology (NICT) and JAXA. It is a 128-element active phased array system operating at 13.8 GHz. The transmitter/receiver (T/R) consists of 128 solid-state power amplifiers and PIN-diode phase shifters. The T/R element is connected to a 2-m slotted waveguide antenna, by which a 2 m × 2 m planar array is constructed. The PR uses a frequency agility technique to obtain 64 (N_s = 64) independent samples with a fixed pulse repetition frequency of 2776 Hz. The PR antenna scans in the cross-track direction over $\pm 17^o$ (215-km swath). The PR performs an external calibration with a ground-based Active Radar Calibrator (ARC) about four times a year and an internal loop calibration to measure the transfer function of the PR receiver about once a day.

The TRMM PR has operated perfectly over the lifetime of the satellite. Instrument calibration has been very steady, with absolute accuracy of less than +/-0.5 dB and long-term relative stability of 0.1 dB. The PR calibration is so steady it has been used as a calibration standard for ground radars. Recently Kojima (2005) has reviewed the reliability of PR with regard to the mission extension. The report states that PR has no moving parts (electrically scanning) affecting instrument lifetime and found that heatpipe and mechanical thermostat components also did not limit mission extension. Total radiation dose for an extended mission is within limits. None of the 128 array elements have failed during the mission and the PR can operate with up to four failures. **Therefore, because there**

is no known component limiting its life, the PR is projected as highly probable to continue operating nominally for the next five years.

TRMM Microwave Imager (TMI). The **TMI is a nine-channel passive microwave radiometer based upon the Special Sensor Microwave/Imager (SSM/I)**, which has been flying aboard the U.S. Defense Meteorological Satellite Program (DMSP) satellites since 1987. The key difference is the addition of a pair of 10.7 GHz channels with horizontal and vertical polarizations, which allowed for the first microwave-based SST measurements. The TMI antenna is an offset parabola, with an aperture size of 61 cm (projected along the propagation direction) and a focal length of 50.8 cm. The antenna beam views the earth surface with an incident angle of 52.8° at the earth's surface. The TMI antenna rotates about a nadir axis at a constant speed of 31.6 rpm. The rotation draws a "circle" on the earth's surface.

The TMI has operated perfectly since TRMM launch. TMI calibration has been steady with no drift or deterioration. Because of its heritage from the SSM/I instruments, TMI lifetime can be projected from SSM/I performance. Of the six SSM/I's launched four are still operating with lifetimes so far of 17, 10, 8 and 5 years. The 85 GHz channel failed on the 17-year instrument two years after launch. Two other SSM/I's were operating at 7 and 9 years when the spacecraft failed in one case and was turned off in the other case. **Thus there is a high probability that the TMI will operate successfully for five years or more.**

Visible and InfraRed Scanner (VIRS). **The VIRS is a five-channel imaging spectroradiometer with bands in the wavelength range from 0.6 to 12 µm.** The VIRS data is used to obtain cloud information using visible and IR techniques in order to provide a cloud context to the microwave-based precipitation retrievals, and also a link to rain estimation techniques and products derived from visible/infrared geosynchronous satellite data. The VIRS has the same center wavelengths and bandwidths as the Advanced Very High Resolution Radiometer (AVHRR) that has flown since 1978 on the National Oceanic and Atmospheric Administration (NOAA) series of spacecraft. The major differences between the two systems are the 2.1-km nadir IFOV and VIRS in contrast to 1.1 km for the AVHRR and the fact that the VIRS has an onboard solar diffuser for post launch calibration of the two reflected solar bands.

The TRMM/VIRS sensor continues to provide reflected solar and thermal emissive radiometry from five spectral bands with nadir spatial resolution of 2 kilometers. Performance has been excellent with exceptional stability in the thermal emissive bands. **Long term trending has revealed only minor response degradations and there is every indication that the VIRS should continue to operate as designed for the foreseeable future.** The non-sunsynchronous TRMM orbit in combination with VIRS' exceptional stability has resulted in the unanticipated use of VIRS as a transfer standard for comparing the radiometric accuracy of imaging radiometers such as Terra and Aqua MODIS, AVHRR and AIRS.

Lightning Imaging Sensor (LIS). **The Lightning Imaging Sensor (LIS) detects all ("total") lightning, since cloud-to-ground, intracloud, and cloud-to-cloud discharges all produce optical pulses that are visible from space.** The LIS consists of an optical staring imager, with a sampling rate slightly greater than 500 frames per second, which identifies lightning activity by detecting momentary changes in the brightness of the clouds as they are illuminated by lightning discharges. Due to the sensitivity and dynamic range of the sensor, it can detect lightning during daytime even in the presence of bright, sunlit clouds. A wide field of view lens, combined with a narrow-band (10 A) interference filter, centered on a strong optical emission mulitplet (OI (1) at 777.4 nm), is focused on a small, high speed 128 x 128 element CCD array. The 80 deg x 80 deg angle field of view, combined with the 400 km altitude, permit the sensor to view clouds within a 600 km x 600 km area of the Earth with a spatial resolution between 3 km (at nadir) for almost 90 sec as TRMM passes overhead. The LIS data products are produced, archived, and reprocessed at and distributed from the Global Hydrology and Climate Center in Huntsville, AL (http://thunder.msfc.nasa.gov).

The LIS continues to provide full functionality. Long term instrument trending indicates that performance continues to be exceptional. **The LIS has no moving parts and because there is no known component limiting its life, it is projected as highly probable to continue operating nominally for the next five years**. The OTD (Optical Transient Detector) precursor mission successfully concluded after five years with the OTD unaffected by any part failure.

4.3 The TRMM Science Data and Information System (TSDIS)

The TRMM Science Data and Information System (TSDIS) is the data processing system for TRMM, producing all the PR, TMI and VIRS, combined and multi-satellite standard products. It produces up to

12GB/day of initial science data from the satellite. TSDIS gets the L0 (raw data with effects of telemetry removed) from the Sensor Data Processing Facility (SDPF). It uses the L0 data to generate the starting level 1 processing L1A (instrument counts reversible to L0). TSDIS personnel interact with the science team algorithm developers (including those in Japan) of L2 and L3 products to incorporate them into the processing stream, ensure that they produce the expected output and provide trending information for analysis. All standard science products are sent to the GSFC Distributed Active Archive Center (DAAC) for the distribution to the general public and for user support for this group. TSDIS also has responsibility for reprocessing TRMM data. The reprocessing requirement is to provide an additional 2X (24GB additional) satellite data reprocessing. Currently, TRMM data is being reprocessed into Version 6 of the standard products. Also, TSDIS produces real-time versions of most of the Level 2 products and the real-time multi-satellite analysis (3B-42RT). In addition to the standard products provided to the wider community, TSDIS also provides the opportunity for science team members to run more specific algorithms on the TRMM data, thus greatly reducing the data infrastructure required by individual PI's. TSDIS, as part of the overall NASA Precipitation Program is evolving into the Precipitation Processing System (PPS) as we move toward GPM. **Current computer hardware will be used during TRMM mission extension, to be replaced just prior to GPM with GPM project funding.**

4.4 Ground validation program

A key component of the TRMM research program is its Ground Validation (GV) effort. A large part of this work has been the careful collection, processing and analysis of ground-based radar data in combination with rain gauge network data. The four primary sites are Darwin, Australia; Houston, Texas; Kwajalein, Republic of the Marshall Islands; and, Melbourne, Florida, with particular emphasis on the Florida and Kwajalein sites. Techniques have been developed and applied to produce carefully quality-controlled ground radar data sets and estimated surface rainfall rates based on the radar data adjusted by quality-controlled rain gauges data. These efforts have resulted in standard validation data sets at both instantaneous and monthly time scales with which to compare TRMM-based rain estimates and have helped to establish the accuracy of the various TRMM products. In addition, other specific gauge data sets were used to produce additional validation products. Recently, significant efforts have been made to utilize polarimetric radar information to develop improved validation data sets. The GV radar and other products have also been used extensively by individual PI's for validation research.

Because of the highly variable nature of precipitation it is important to have both high quality validation data and a variety of locations and time periods. The number of sites is limited due to the need for high quality data and the logistical demands of producing the validation products. Therefore, it is imperative for the validation products to cover various seasons and inter-annual variations to provide the natural variability in precipitation amounts and other characteristics with which to test the satellite estimates. **For these reasons the TRMM GV program has continued to collect and process data and should continue to do so in the future as the validation effort evolves into the broader validation program of GPM.**

5. CONTROLLED RE-ENTRY ISSUE

The TRMM spacecraft has sufficient mass and types of material so that it is estimated that not all of the satellite will vaporize during re-entry into the Earth's atmosphere. **The estimated cross-section of the orbital debris that would survive re-entry is 11 m^2. This cross-section converts to a probability of injury of 1/5,000, when population density is taken into account.** NASA guidelines state that an orbital reentry risk level of 1 in 10,000 (roughly equivalent to 8 m^2) is acceptable.[1] Therefore, TRMM is over the threshold and is a candidate for possible controlled re-entry into the Pacific Ocean to minimize the probability of human injury.

Table 4 shows the volume multiplied by mass (first column) for a selection of satellites and the estimated orbital debris cross-sections as estimated by Johnson Space Center's ORSAT program. TRMM's numbers are typical of moderate size satellites. Some of the satellites larger than TRMM (e.g., Aqua) that are above the threshold have received a waiver from doing a controlled re-entry. The Gamma Ray Observatory (GRO) underwent a controlled re-entry during the 1990's. Uncontrolled re-entry of objects the size of TRMM are not uncommon. For example, *in 1999, 111 large objects reentered Earth's atmosphere uncontrolled* (Martin, 2002). Twenty-one of the objects were

[1]See NASA Policy Directive 8710.3B *NASA Policy for Limiting Orbital Debris Generation* and NASA Safety Standard 1740.14 *Guidelines and Assessment Procedures for Limiting Orbital Debris*.

satellites and the remainder were primarily rocket bodies used to launch satellites. Twenty-nine of the 111 objects originated from the United States and NASA was responsible for six of these 29 objects.

In a 2002 TRMM Disposal Risk Review (Martin, 2002), NASA's Office of Safety and Mission Assurance concludes, **"In the case of a TRMM uncontrolled reentry, the casualty risk of 2/10,000 is in an intermediate, or tolerability zone, where the risk may be tolerated in return for other (public safety) benefits."** In addition, the report states "Barring any impediments from NASA Legal Council, it is concluded that a **decision to accept the uncontrolled reentry public safety risk of TRMM, in exchange for extending the mission and potentially benefiting from the improvement in storm analysis and forecasting capabilities, is reasonable** and within the discretion of the Earth Science Enterprise and the NASA Administrator."

TRMM's propulsion system is used to maintain its relatively low orbit against drag. Currently, orbit maneuvers are performed every three weeks using about 1.2 kg of fuel each time. As of March 1, 2005 TRMM is estimated to have 145 kg of fuel remaining. 138 kg of fuel is required for controlled re-entry. *The fuel threshold, therefore, is only months away*. Fig. 14 shows the recent fuel history and forecast for the future based on solar forecasts. If all the remaining fuel is used for orbit maintenance, *TRMM has the potential to stay on station doing science until 2012*. The controlled re-entry, if it were to occur, would happen after the satellite drifts down from 400 km to 320 km for re-entry initiation. This drift-down period would take approximately 1.5 years. *Full science operations would cease within a few months of starting drift-down*, due to the requirement for orbit altitude maintenance with small tolerance for the PR.

Satellite Debris Estimate Summary

Satellite	**L x W x D x M (m^3-kg)**	**Debris Estimate (m^2) ORSAT**
HST	-	75
GRO	4.8 X 10^5	52
UARS	2.8 x 10^5	22
Terra	1.2 x 10^5	-
Aqua	4.9 x 10^4	19
Aura	4.9x 10^4	11
TRMM	4.7x 10^4	11
LS-7	2.6 x 10^4	-
NPP	2.5 x 10^4	-
ERBS	3.0 x 10^4	-
EUVE	2.4 x 10^4	6

Table 4. Volume x mass and estimated orbital debris cross-section values for various missions.

6. BUDGET

Over the last few years TRMM budgets have been reduced in preparation for mission extension. Mission flight operations support is now through Capitol College allowing for student involvement and significant cost savings. At the same time the ground system is being replaced by a more automated system, which will be used as a prototype for other missions (e.g., Terra, Aqua and Aura). **These changes in the TRMM mission flight operations have reduced costs by 40% from FY 2003 to below $4M/yr (full cost) for the years FY 06-09**.

Science data processing (TSDIS) operations have also been streamlined over the same period with similar cost savings and a current cost of about $3.7M/yr. Over the next few years as TRMM continues, a new software processing system (PPS) will be developing (under separate budget) to support GPM and the overall Precipitation Program. A transition will occur where PPS will be used to produce some or all TRMM products. For example, TRMM Version 7 products may also be designed to be Version 1 of GPM, produced with the PPS system, run on TRMM-funded computers. Version 7 may be produced in 2007 or 2008. This transition from TSDIS to PPS will allow for efficient continuation of production of precipitation products going from TRMM to GPM in a cost effective manner. Even if TRMM flight operations cease, TSDIS funding will continue at substantial levels (see guideline in Table II of budget) to reprocess TRMM data, continue production of the multi-satellite product, and transition into the GPM era.

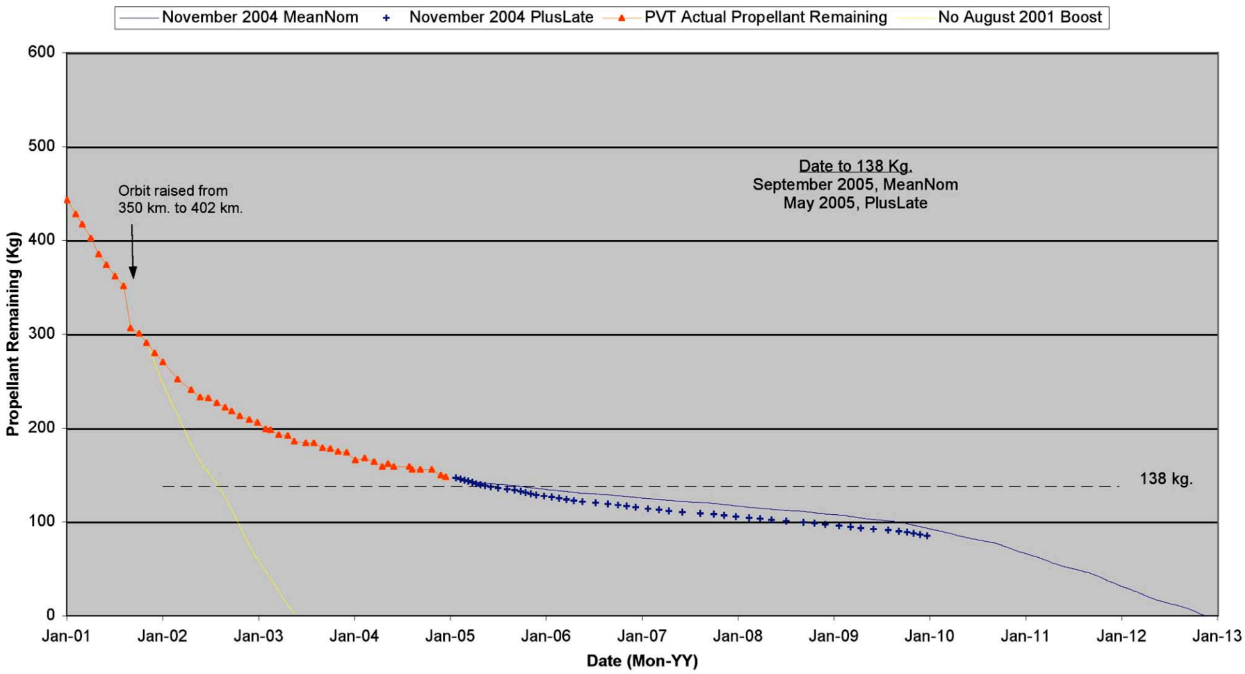

Fig. 14. Fuel levels aboard the TRMM satellite and projected rate of decrease (November 2004 projections). The horizontal line marked "138 kg" indicates the critical fuel level below which reentry cannot be controlled. The extension of the lifetime of TRMM due to the orbital boost in 2001 is evident from the difference between the original projected zero fuel point in 2003 and the nominal curve (solid line) that intersects zero in 2012. The crosses are for the 2 sigma plus flux and late phase.

Since 2003 TRMM no longer has a separate science team. Instead, **TRMM-related science is accomplished under the Precipitation Measurement Missions (PMM) Science Team**, which combines science activities related to TRMM and the forthcoming Global Precipitation Measurement (GPM) mission. PMM science funding has decreased over the last few years as TRMM validation and field experiment activity has decreased after the first five years of the mission. An additional decrease of approximately 15% has occurred for FY 2005. Approximate level science funding is shown for the 2006-09 period in the following budget sheet. **This proposed PMM funding covers research using TRMM observations (and other current observations) and the necessary science development for GPM. Even if TRMM flight operations cease, PMM Science Team funding continues (see guideline in Table II of budget) at a substantial level.**

Budgets for LIS operations, data processing and science through MSFC are carried in the following budgets as separate lines, because LIS is an EOS instrument and is funded separately from TRMM and the Precipitation Program.

In summary, extension of TRMM is inexpensive relative to the NASA guidelines (see Table II and V in budget sheet). **With PMM Science Team and TSDIS funding already substantially covered in the guidelines, the primary additional cost is to TRMM flight operations (less than $4M/yr).** Flight operations costs would continue into FY 07 even if a re-entry is required. LIS funding is also additional. Therefore, the multi-year extension of TRMM, including the critical science and applications to be achieved for the NASA program, and the potential overlap with GPM, can be achieved with a very modest increase to the TRMM budget. **The option to extend TRMM obviously has a very high payoff for science and applications and also has a very low additional cost (less than $4M/yr) for NASA.**

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Education / Public Outreach Summary and Planned Activities
Senior Review 2005 - Tropical Rainfall Measuring Mission (TRMM)

Jeffrey B. Halverson - TRMM Education and Outreach Scientist

1) Outreach Philosophy

Since the launch of TRMM in November 1997, the education and public outreach (E/PO) program has disseminated a wide range of products (datasets, visualizations, science highlights), utilizing a variety of resources (printed media, video, DVD and world wide web, television outlets, and museums), to target a diverse audience (middle and high school, undergraduates, general public). TRMM E/PO has emphasized the following themes: 1) the spectrum of TRMM science encompasses space and time scales ranging from microscopic interactions of cloud particles that give rise to rain, to the behavior of familiar storm systems such as hurricanes, to global/interannual shifts in rainfall patterns that accompany El Nino; 2) TRMM is much more than just measuring rainfall, emphasizing the connection between rain and energy in the atmosphere, rain and lightning, rainfall and aerosols/atmospheric pollutants, and links between ocean surface temperature and precipitation; and 3) TRMM plays a unique science role but complements the larger constellation of NASA, NOAA and military space orbiters, both as a calibrator and as a provider of measurements designed to better understand Earth's complex cycling of energy and water.

2) Synopsis of Achievements to Date (1997-2005)

TRMM Website (http://trmm.gsfc.nasa.gov): Beyond science and mission information, the website is a vital tool for formal, informal, stakeholder, and public education and outreach. This cornerstone of TRMM E/PO provides an up-to-date collection of (a) formal education materials, (b) current maps of global rainfall accumulation, (c) archived visualizations of extreme rain events (such as flash floods and tropical cyclones) with accompanying descriptions, (d) links to TRMM datasets, and (e) a database of published TRMM research papers. Our global rain maps are the centerpiece of the home page, and these maps are updated every three hours (Figure 1). No other website provides such a comprehensive snapshot and 7-day history of rainfall at relatively high resolution (0.25 x 0.25 degree) and near-global coverage. Other pages on the TRMM website guide the user to images depicting the latest rainfall perturbations induced by El Nino and La Nina, maps showing areas of dangerous flood potential based on rain history and rain rate, and three-dimensional rain structure in active tropical cyclones around the world. We regularly port TRMM observations on landfalling tropical cyclones and catastrophic floods directly to NASA's Earth Observatory (EO) website (http://earthobservatory.nasa.gov). EO has greatly improved the visibility and accessibility of TRMM products as they regularly feature our visualizations and descriptions of natural events in both the Natural Hazards and Image of the Day sections.

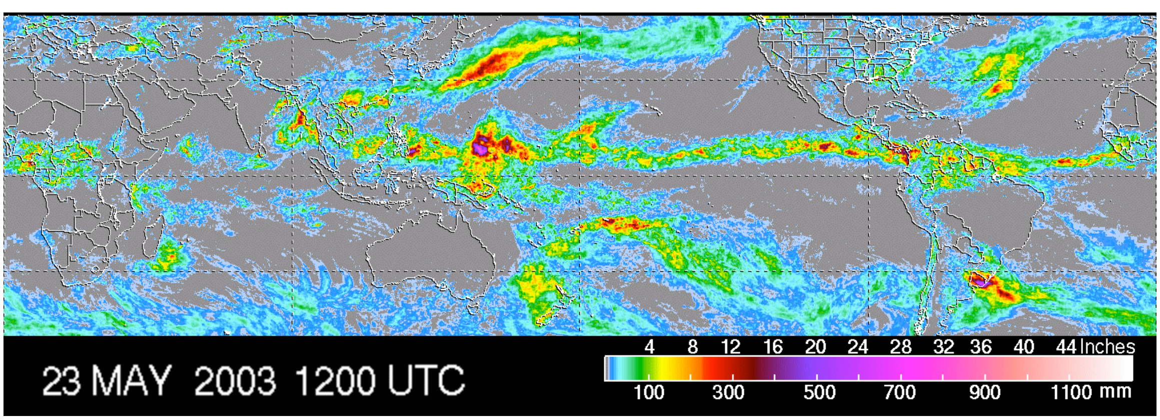


Figure 1: Example of global, near-real time rain accumulation as shown on the TRMM website.
Media Outlets:

The TRMM E/PO scientists (Halverson and his predecessors) have helped NASA Goddard and Headquarters Public Affairs draft more than 50 press releases since 1998. Articles highlighting TRMM science findings on urban rainfall have appeared in *Time* magazine. An article featuring TRMM visualizations of Atlantic hurricanes will appear in the August, 2005 issue of *National Geographic*. Dr. Halverson writes a monthly column in *Weatherwise Magazine* that frequently highlights the TRMM satellite and other NASA remote sensors such as MODIS. Chapters describing the state of science in global rainfall and tropical cyclones will appear in a mass-market Earth science book to be published by Cambridge University Press, and will prominently feature images from TRMM (Figure 2). During the active Atlantic hurricane seasons of 2003 and 2004, Drs. Marshall Shepherd (past TRMM E/PO scientist) and Halverson described how TRMM was revolutionizing the way we understand hurricanes on national television. The media tour included appearances on more than 60 local television networks, CNN, Larry King, NOVA and The Discovery Science Channel. To support the appearances, several 3D signature visualizations of Hurricanes Isabel, Frances, Charley and Ivan were created by the Goddard Scientific Visualization Studio (SVS). These treatments showed millions of viewers how TRMM effectively "sees through" the clouds of hurricanes, identifying the pattern of rain (much like taking a CAT scan) and how the structure provides clues about storm intensity change. The comprehensive set of visual treatments utilized in our 2003-2004 media campaign are located at http://svs.gsfc.nasa.gov.

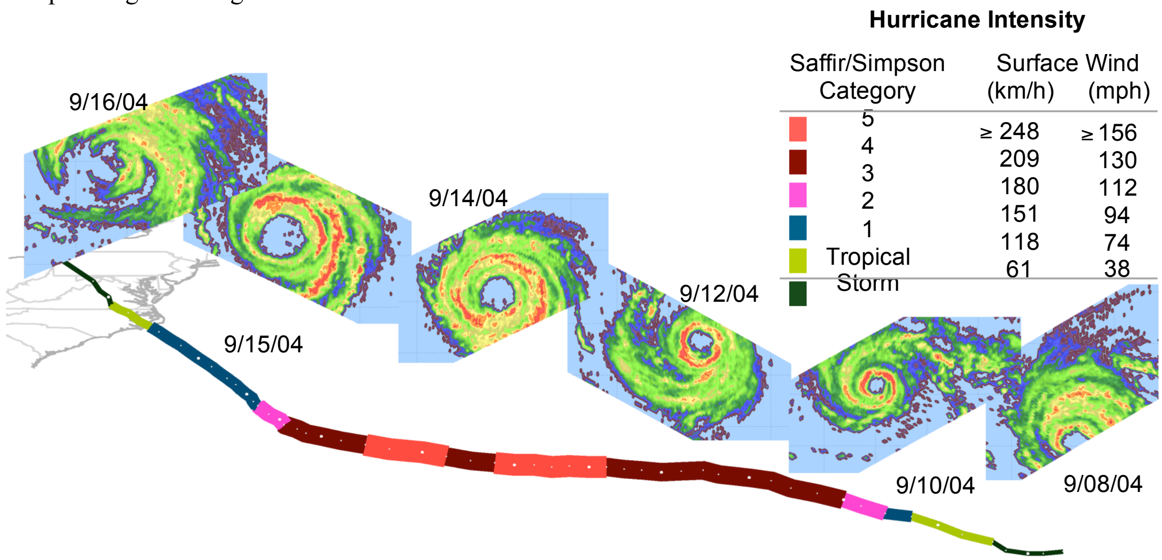


Figure 2: Mosaic of TRMM overpasses of Hurricane Isabel crossing the Atlantic.

Formal and Informal Educational Resources Targeting K-16 and General Public:

A series of inquiry-based formal education modules in support of TRMM and titled "Investigating the Climate System" was commissioned from the Institute for Global Environmental Strategies (IGES). These modules, which highlight Clouds, Energy, Precipitation, Weather and Winds, are separately downloadable from the TRMM website. These materials include teacher's guides, lessons and activities with supporting animations. In addition, downloadable educational models on rainfall-climate, hurricanes, lightning and the water cycle were developed in collaboration with Mrs. Leslie Bridgett, a teacher from Charles County, MD and TRMM-based modules were developed in collaboration with Mrs. Annette de Charon at the Gulf of Maine Aquarium.

For informal public education, a 20-min video titled "Tropical Rainfall: Earth's Invisible Engine" was produced in collaboration with Jim Lynch and Associates. The video presents an overview of the TRMM mission, the types of observables collected by the satellite, and a sampling of key science findings. In 2004, the video was updated with a DVD, produced in-house. The DVD contains over an hour of narrated science stories, targeting a general audience. The goal of the DVD is to illustrate TRMM's contributions to understanding global rainfall variability, the central role of tropical rainfall in the global atmospheric water and energy cycle, and the rainfall-energy connection in powering tropical cyclones. Ten science vignettes, each 1-2 minutes in length and downloadable from the TRMM website, distill these three broad scientific themes into smaller learning topics (such as the connection between global rainfall and lightning or the relationship between global cloud cover and rain intensity). These vignettes are useful enabling tools for educators and students alike.

For three years at NASA GSFC, undergraduates have had the unique experience of experiencing first-hand the complex task of maintaining satellites in orbit, including TRMM, under a grant sponsored by the Space Operations

Institute of Capitol College. The students learn how to perform routine TRMM orbit-maintaining operations in the NASA GSFC control center and work side-by-side with professional controllers. They load memory, download data recorders and perform trending and analysis calculations. In addition to becoming certified in satellite operations, Capitol College attempts to place the students into control-related careers in the satellite missions support industry.

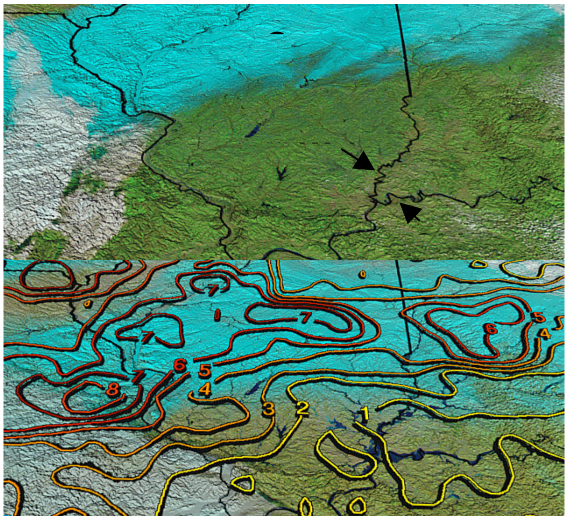
The current TRMM E/PO scientist has lectured to groups of Earth science teachers at Goddard workshops, has engaged students in science distance learning utilizing the video classroom, and has presented TRMM science highlights to numerous universities. TRMM visualizations have been featured in presentations at the Science Museum of Minnesota under the direction of Dr. Alan Nelson. A unique animation of Earth data, called Earth Today, is on exhibit at the National Air and Space Museum. The animation, narrated by James Earl Jones, is continuously updated with the most current rainfall data provided by TRMM and other sensors. Earth Today provides a powerful means of engaging the public in the current state of the planet and shows the important connection between rainfall and other geophysical datasets.

3) TRMM E/PO Plan for 2006-2009

The TRMM E/PO group at NASA Goddard will continue our mission of broadly disseminating TRMM highlights and scientific findings using the spectrum of tools identified above (i.e. media campaigns, popular magazines, DVD, website, museums, invited lectures and talks). An essential component will be maintaining student involvement in the Capitol College satellite missions support program. However, there are several thematic changes to E/PO which will be required to transition TRMM E/PO into the Global Precipitation Mission (GPM) era. GPM is the follow-on for TRMM, consisting of a constellation of satellites, targeted for launch in 2010. GPM will expand precipitation measurement out of the tropics and subtropics into high latitudes and will provide 3-hourly rainfall observations. The mandate of E/PO will be to become less mission-centric, and concentrate instead on the global-scale measurement and science of precipitation from space, including frozen forms of precipitation such as ice and snow. Our existing focus of TRMM in the tropics and subtropics will be meshed with extratropical precipitation processes such as fronts and migrating storms in the jetstream. These processes impact a great number of people across North America, Europe, Asia every day throughout the year, as opposed to the occasional tropical cyclone in the fall season or an active El Nino year. A step in this more globally integrated direction is already in place in the form of the TRMM-based Multi-Satellite Precipitation Analysis (MPA, Figure 1) which features prominently on our web site. In addition, ongoing and parallel efforts to quantify longer-term global rainfall variability, such as the Global Precipitation Climatology Project (GPCP), will be blended under the umbrella of a more precipitation-centric outreach effort.

Secondly, our E/PO efforts are engaged in identifying more effective ways at conveying the concept that rainfall, while an important geophysical entity in its own right, can not be treated in isolation of the larger Earth water cycle and Earth systems. In the GPM-era, more emphasis will be placed on the societal impacts of rainfall - such as devastating floods, the impact of rainfall on soil moisture, agriculture and the health of ecosystems, and freshwater management. Our education and outreach efforts should reflect this shift in paradigm - how can we identify ways in which "precipitation science better serves society?" By adopting a more holistic or Earth Systems framework, we will combine TRMM/GPM datasets and visuals with remote sensors that graphically portray the aftermath and consequences of heavy rain input into watersheds. An example of this type of dataset fusion is shown in Figure 3 for heavy winter rains which recently inundated the upper Midwest. We will seek to partner with other agencies and organizations that have expertise in the watershed response to heavy rain, such as the Dartmouth Flood Observatory (http://www.dartmouth.edu). TRMM/GPM rain accumulation products can be merged with maps of regional and widespread flooding, estimates of river stage and discharge, and maps of rapid response inundation. In addition, we are exploring ways of partnering with joint NASA-NOAA-USGS efforts to better identify regions that are prone to deadly landslides, such as the Caribbean and Central America. An important component of TRMM/GPM outreach will be to illustrate and identify regions where torrential rainfall coincides with landslide vulnerability. Space-based monitoring and web-based dissemination of this information can serve as a powerful educational tool to warn of susceptibility.

Figure 3: MODIS before (Nov 25, 2004) and after (Jan 17, 2005) images of swollen Ohio and Wabash Rivers (arrows). TRMM-based MPA rain accumulation is overlaid on bottom panel.



Thirdly, we are prototyping a means by which visualizations of TRMM Precipitation Radar data can be more effectively utilized by the public, research and operations communities. There is a wealth of potentially useful information on rainfall vertical structure in hurricanes, but these data have not been available in real time. Our prototype (Figure 4) provides near-real time analysis of PR data in an interactive, animated, 3D format. The visualization tool utilizes a simple interface that will allow scientists, graduate and undergraduate students and the public to better understand tropical cyclone structure the data-sparse oceans. Oftentimes, key structural clues - such as extremely tall convective rain clouds in the eyewall (Figure 4, below) - portend sudden intensification of the storm. The product will be automatically generated during each TRMM overpass of an active named cyclone anywhere in the world. Plans are underway to partner with the Naval Research Laboratory's Tropical Cyclone website, which provides the best single source of satellite data for tropical cyclones around the globe. This will ensure timely, reliable and name-brand dissemination of TRMM visualizations to a much broader audience than is currently possible, with the potential for operational implementation by forecasters at the Tropical Prediction Center.

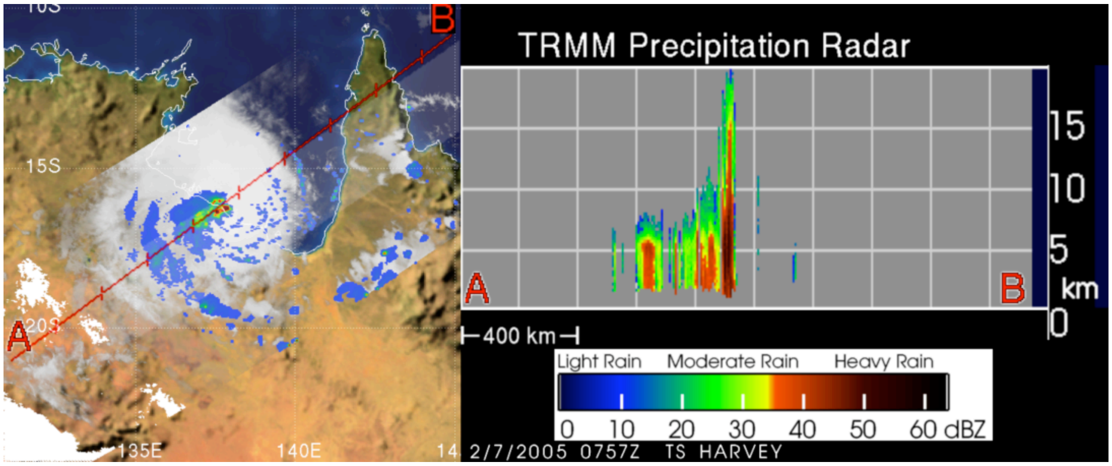


Figure 4: Analysis frame taken from 3D TRMM precipitation radar movie showing rain intensity and vertical structure in Tropical Storm Harvey. Extremely tall convective tower (20 km high) was associated with severe damage produced by the storm as it moved onshore.

Appendix A - Acronyms

AMMA	African Multi-Disciplinary Monsoon Analysis
AQUA	Satellite of NASA's Earth Observing System (EOS), Latin for "water"
AQUA/AMSR	Satellite of NASA's Earth Observing System (EOS)/Advanced Microwave Scanning Radiometer
AMSR	Advanced Microwave Scanning Radiometer
AMSU's	Advanced Microwave Sounding Units
ARC	Active Radar Calibrator
AURA	Satellite of NASA's Earth Observing System (EOS), Latin for "Air"
AVHRR	Advanced Very High Resolution Radiometer
BAMS	Bulletin of the American Meteorological Society
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CERES	Clouds and Earth Radiant Energy System
CCSP	Climate Change Science Program
CKE	Cumulus Kinetic Energy
CLIVAR	Climate Variability and Predictability Research
CLOUDSAT	Cloud Satellite
DAAC	Distributed Active Archive Center
DMSP	Defense Meteorological Satellite Program
DSD	Drop Size Distribution
DSDs	Drop Size Distributions
DVAR	Dimensional Variation Assimilation System
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
FTP	File Transfer Protocol
GEWEX	Global Energy and Water Cycle Experiment
GLDAS	Global Land Data Assimilation System
GPCP	Global Precipitation Climatology Project
GRO	Gamma Ray Observatory
GV	Ground Validation
JAXA	Japan Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
LIS	Lightning Imaging Sensor
MCS	Mesoscale Convective System
MCSs	Mesoscale Convective Systems
MJO	Madden-Julian Oscillation
MJOs	Madden-Julian Oscillations
MLS	Microwave Limb Sounder
MPA	Multi-satellite Precipitation Analysis
NA	National Academies
NASA	National Aeronautics and Space Administration
NASA/NOAA/DOD	National Aeronautics and Space Administration/National Oceanic and Atmospheric Administration/Department of Defense

NICT	National Institute of Information and Communication Technology
NOAA	National Oceanic and Atmospheric Administration
NOAA/NCEP	National Oceanic and Atmospheric Administration/National Centers of Environmental Prediction
ORSAT	Object Re-entry Survival Analysis Tool
OTD	Optical Transient Detector
PMM	Precipitation Measurement Missions
PPS	Precipitation Processing System
PR	Precipitation Radar
SADA	Solar Array Drive Actuators
SAL	Saharan Air Layer
SIGMETs	Significant Meteorological Advisories
TCSP	Tropical Cloud Systems and Processes
TERRA	NASA's Earth Observing System (EOS) flagship satellite, Latin for "Land"
TES	Tropospheric Emission Spectrometer
TEXMEX	Tropical Experiment in Mexico
THORPEX	The Observing-System Research and Predictability Experiment
T/R	Transmitter/Receiver
TraP	Tropical Rainfall Potential
TRMM	Tropical Rainfall Measuring Mission
TMI	TRMM Microwave Imager
TSDIS	TRMM Science Data and Information System
TTL	Tropopause Transition Layer
SDPF	Sensor Data Procession Facility
SSM/I	Special Sensor Microwave/Imager
SST	Sea-Surface Temperature
SSY	Small-Scale Yielding
VIRS	Visible and Infrared Scanner
WCRP	World Climate Research Program

Appendix B - Description of TRMM Rain Algorithms

TMI Surface Rain and Profiling Algorithm - (2A-12): The TMI profiling algorithm (often referred to as GPROF [Goddard Profiling]) makes use of the Bayesian methodology to relate the observed multi-channel brightness temperatures to the hydrometeors provided in an a-priori database. This initial database is supplied by non-hydrostatic cumulus-scale cloud models using explicit cloud microphysics. By taking a large number of simulations and a number of time steps within each simulation, a fairly robust set of possible cloud realizations is created. Radiative transfer computations are then used to compute brightness temperatures (T_b). These T_b are finally convolved with the known antenna patterns of the TMI to generate the corresponding T_b the satellite would observe. In the Bayesian approach, the RMS difference between observed and modeled T_b are used to assign weight to each cloud model profile in the a-priori database to derive new composite profile. The basic technique is described in more detail in (Kummerow et al. 1996, 2001).

The output product from 2A-12 consists of the surface rainfall rate, convective rain fraction, and a confidence parameter, as well as the 3-D structure using 14 vertical layers. There are four hydrometeor classes (rainwater, cloud water, precipitation-size ice, and cloud ice). While the structure information may not be as detailed as that which can be obtained from the PR instrument, the much wider swath of the TMI makes this product important for climatological purposes. Over land, where the emission signature of rain water cannot be detected directly, a semi-empirical relation based upon climatological rainfall derived from the TRMM PR and ground measurements is used.

PR Surface Rain and Profiling Algorithm - (2A-25): The primary objective of 2A-25 is to produce the best estimate of the vertical rainfall rate profile for each radar beam from the TRMM PR data. The 2A25 algorithm retrieves the precipitation profiles in two steps. It estimates the true effective reflectivity factor (*Ze*) from the measured vertical profiles of reflectivity factor (*Zm*) first, and then converts the estimated *Ze* into the rainfall rate (*R*). The step to estimate *Ze* from *Zm*, which corresponds to the attenuation correction, is carried out by using a hybrid method described in Iguchi and Meneghini (1994). The path-integrated attenuation (PIA) is estimated in such a way that it conforms to the PIAs from both the surface reference technique (2A-21) and the Hitschfeld-Bordan method when the relative accuracy of the methods is taken into account in a given circumstance. The estimated *Ze* is then converted into *R* by using an appropriate *Ze-R* relationship, which is adjusted according to the rain type, the altitude, and the correction factor used in the hybrid method of attenuation correction. Both the attenuation corrected *Ze* and the rainfall rate estimate *R* are given at each resolution cell (4 km × 4 km × 250 m) of the PR.

Combined PR/TMI Surface Rain and Profiling Algorithm (2B-31): The guiding principle in the design of the combined algorithm was to merge information from the two sensors into a single retrieval that embodied the strengths of each sensor. The algorithm uses all the channels of the TMI to compare the candidate rain profiles, retrieved from the radar using different drop size distribution (DSD) assumptions, and quantify how consistent their radiances would be with the measured brightness temperatures.

A parameterization of the drop size distribution (DSD) using three mutually independent parameters is used. These are a) a quantity parameter R (the rain rate), and the two shape parameters D' and s', the first proportional to the mass-weighted mean drop diameter and the second proportional to the relative standard deviation of diameters about this mean. This parameterization produces *Z-R* and *k-R* relationships, which are indexed by the shape parameters. Within a given TMI footprint, one has multiple profiles of measured radar reflectivities. For twelve different settings of the shape parameters *Z* is inverted into a rain profile R. Parameterized forward radiative transfer formulas are used to derive the radiance that one would expect each rain profile to produce. These radiances are combined according to the position of the radar beam within the TMI footprint to synthesize the brightness temperature T that one would expect. The latter is then compared to the measured brightness temperatures T_b, and a weight w is derived to be used in averaging the rain rates corresponding to the different possible shape parameters . It is assumed that the DSD shape parameters are uniform in altitude and within the radar beam (Haddad et al. 1997).

Monthly Statistical TMI Surface Rain Algorithm (3A-11): The 3A11 algorithm produces monthly oceanic rainfall accumulations and other rain rate parameters on a 5º x 5º grid. It is used in addition to monthly accumulations of the instantaneous (level 2) algorithms. The algorithm, originally developed for SSM/I, is a statistical/physical algorithm that corrects for the monthly sampling and beamfilling biases (Wilheit et al. 1991, Chang and Chiu 1998). It is based on a rain rate-Tb relation derived from an atmospheric model that is completely specified by the rain intensity and the height of the zero degree isotherm (freezing height). The freezing height acts as a proxy of the integrated columnar water vapor. A combination channel of twice the 19 GHz minus the 21 GHz vertical polarization of TMI is used to minimize the effect of water vapor variability on the microwave rain signature. Monthly rain rates are modeled by a mixed log-normal distribution (Kedem et al. 1990). Monthly histograms of TMI and the combination channel Tbs are computed and fitted to a mixed log-normal rain rate distribution via the rain rate-Tb relation to correct for inadequate sampling. To account for the beam-filling error, the derived TMI rain-rate indices are then multiplied by a correction factor that is dependent on rain rate variability and the freezing height (Chiu et al. 1990, Wang, 1995). The functional dependence of the beamfilling correction on freezing height is based on model simulation using airborne radar observations.

Multi-satellite Surface Rain Algorithms (3B-42, 3B-43): Multi-satellite algorithms have been part of the TRMM set of standard algorithms since launch. Originally, the multi-satellite algorithm used TRMM information (the combined PR/TMI 2B-31 algorithm) to calibrate rain estimates from geosynchronous IR observations (Adler et al. 2000). In the current Version 6 processing the 3B-42 algorithm is the TRMM-based Multi-satellite Precipitation Analysis (MPA) (Huffman et al. 2003). The MPA is a quasi-global precipitation analysis at fine time and space scales (3-hr, 0.25° × 0.25° latitude–longitude) over the latitude band 50°N-S. This analysis scheme makes use of TRMM's highest quality, but infrequent observations, along with high quality passive microwave-based rain estimates from 3-7 polar-orbiting satellites, and even estimates based on the five geosynchronous IR data covering the tropics. The combined quasi-global rain map at 3-hr resolution is produced by using TRMM-based estimates (algorithm 2B-31) to calibrate, or adjust, the estimates from all the other satellites, and then combining all the estimates into the MPA final analysis. The technique uses as much microwave data as possible, including data from Aqua/AMSR and SSM/I's and AMSU's on operational satellites, and only uses the geo-IR estimates to fill in remaining gaps in the three-hour analysis. The calibrations are computed using monthly accumulations of matched data to ensure stability. A standard monthly estimate (product 3B-43) is calculated by incorporating monthly gauge information over land to adjust the satellite estimates over land. When the Version 6 re-processing is finished 3B-42 will provide a 3-hr resolution surface rainfall product for the entire TRMM period (January 1998-present). A similar, real-time version of the 3-hr MPA merged product is available on the U.S. TRMM web site (trmm.gsfc.nasa.gov) a few hours after observation time.